

**Growth, Survival, and Microclimate of
Conifers Planted within Forest Gaps:
Results for the First Five Growing Seasons**

2013



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Peter Fielder



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ABSTRACT

This report describes the establishment of three 0.5-ha gaps and the measurement of two until the end of the 2010 growing season. Three study sites were established on eastern Vancouver Island to explore the effect of stand edge on the growth of four species of conifers with different shade tolerance rankings. One light study gap was planted at the Snowden Demonstration Forest (GS10) in 2004, another near Elk Bay (HU10) in 2006, and a third at Gray Lake (PP10) in 2009. All study sites are within 40 km of Campbell River. Funding restrictions prevented light estimates from being made at the Gray Lake site; therefore, only growth measurements have been possible at that site. At GS10 and HU10, the light environment of each seedling was characterized using hemispherical photographs. In addition, instruments were installed to measure transmittance of above-canopy light (T), temperature, rainfall, soil moisture, and vapour pressure deficit across both gaps. Data for at least five growing seasons (April 1–October 31) are presented for both sites. Maximum T at GS10 and HU10 was approximately 0.8 and 0.7, respectively, and minimum levels in the understorey declined to less than 0.05 at both sites on the south side of the gaps. Growth on the sites was affected by both soil moisture and vapour pressure deficit. An additive model was used to incorporate the moisture variables with T estimates to model the effect of light on growth, although replication was considered insufficient for statistical comparisons between the two sites. Growth tended to increase to a maximum at T values of approximately 0.3 and 0.8 for western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western redcedar (*Thuja plicata* Donn.), respectively, and did not reach a maximum at approximately 0.8 above-canopy light for Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) and western white pine (*Pinus monticola* Dougl.). Light modelling with TASS III revealed both differences and similarities between the modelled values and estimates derived from hemispherical photos.

These microclimate and light assessments suggest that conifer seedling growth is a function of a combination of light, moisture, and temperature conditions that change depending on site and proximity to the residual stand and position within gaps. These early 5-year results indicate that a group selection system with gaps smaller than 0.5 ha may not provide adequate light for less shade-tolerant species such as Douglas-fir and western white pine to outcompete more shade-tolerant species such as western hemlock and western redcedar but that moisture differences can help compensate for lower light levels. Continued monitoring of these two sites along with additional gap studies will provide valuable information from which to explore forest gap regeneration dynamics and improve science-based decision-making regarding partial cutting silvicultural systems.

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*Dedicated to the memory of Steve Dolphin,
who worked on this project as a co-op student in 2007*

CONTENTS

Abstract	iii
Acknowledgements	iv
1 Introduction	1
1.1 Background	1
1.2 Objectives	2
2 Methods	2
2.1 Site Description	2
2.2 Experimental Design and Site Layout	5
2.2.1 Planting at GS10, HU10, and PP10	7
2.3 Light Modelling	7
2.3.1 Light modelling using the Spot Light Interceptance Model ..	9
2.3.2 Light modelling using TRAYci	9
2.4 Climate and Microclimate Measurements	9
2.4.1 Light measurement	10
2.4.2 Other microclimate measurements	12
2.5 Seedling Measurements and Growth Modelling	14
2.6 Data Recording and Storage	15
3 Results	15
3.1 Climate	15
3.1.1 Photosynthetic photon flux density	15
3.1.2 Vapour pressure deficit	18
3.1.3 Rainfall	18
3.1.4 Air temperature	21
3.1.5 Soil temperature	21
3.2 Microclimate Monitoring	24
3.2.1 Light monitoring	24
3.2.2 Soil moisture monitoring	25
3.2.3 Hourly air temperature, and calculation of vapour pressure deficit and evaporative demand period	28
3.3 Estimates of Growing-season Light	29
3.3.1 Gap sensors and correction of hemispherical values	29
3.4 Seedling Measurements	35
3.4.1 Western hemlock	38
3.4.2 Western redcedar	43
3.4.3 Douglas-fir	49
3.4.4 Western white pine	50
3.5 Modelling of Growth in Response to Gap Conditions	51
3.5.1 Western hemlock	57
3.5.2 Western redcedar	57
3.5.3 Douglas-fir	58
3.5.4 Western white pine	58
4 Discussion	59
4.1 GS10 Gap at STEMS 1	59
4.2 HU10 Gap at STEMS 2	62
4.3 TASS III Estimates	64

5 Summary	64
6 Conclusion	66
Literature Cited.	67

APPENDICES

1 Species and stock types planted in the three light study gaps	72
2 TASS III settings to run TRAYci (light model)	73
3 Seedling measurement variables	74
4 Example of SAS code used in growth modelling	76
5 Data recording and collection for EP1213	77
6 Vegetation control at the light study gaps	79
7 Partial residual Plots	80

TABLES

1 Map co-ordinates of the light study gaps and associated climate stations	3
2 Predicting missing height and crown height values from breast height diameter for all numbered residual trees at GS10 and HU10 ..	9
3 Equations derived from the relationship between quantum sensor and hemispherical estimates of transmitted above-canopy light for the 13 sensor points at both GS10 and HU10 gaps	12
4 Annual and growing-season sums of photosynthetic photon flux density and rainfall for years 2004–2009 at STEMS 1 and 2006–2010 at STEMS 2	18
5 STEMS 1 annual and growing-season data summaries for air and soil temperatures and vapour pressure deficit	19
6 STEMS 2 annual and growing-season data summaries for air and soil temperatures and vapour pressure deficit	20
7 Annual seedling growth means and standard deviations, and browsing damage for the first 5 years in the GS10 light study gap at STEMS 1	36
8 Annual seedling growth means and standard deviations for the first 5 years in the HU10 light study gap at STEMS 2	37
9 General additive model parameter estimates and significance tests for the relationship between log stem volume increment and average corrected annual transmittance of above-canopy light, soil moisture deficit period, and evaporative demand period at the GS10 and HU10 light study gaps	52
A1.1 Species, seedlot, and stock type information for seedlings planted in the GS10, HU10, and Gray Lake light study gaps	72
A2.1 TASS III settings to run TRAYci and predict growing-season T values for the GS10 and HU10 gaps	73
A5.1 Types of data, variables used, nature of raw data, and modified and summary files	77
A6.1 Vegetation control at each light study site	79

FIGURES

1	Location of STEMS study sites on eastern Vancouver Island.	3
2	Light study gaps before planting: STEMS 1 in 2004 and STEMS 2 in 2006, viewed from the northeast corner; and STEMS 3 in 2009, viewed from the eastern edge.	4
3	Light study gap showing mapped locations of residual trees, planted seedlings, quantum sensors, and soil moisture sensors at STEMS 1 ...	8
4	A custom-made quantum sensor employing a gallium arsenide phosphide photovoltaic cell; a line of quantum sensor posts, looking north; and an individual proprietary quantum sensor on a post with levelling plate.	10
5	STEMS 2 communications mast, main climate station in HU10 gap, and interior of the main enclosure.	11
6	Temperature sensors under the north canopy at HU10.	13
7	STEMS 1 mast climate data from 2004 to January 2009: daily photosynthetic photon flux density; daily vapour pressure deficit; and daily rainfall.	16
8	STEMS 2 mast climate data from 2006 to January 2010: daily photosynthetic photon flux density; daily vapour pressure deficit; and daily rainfall.	17
9	STEMS 1 climate data from 2004 to January 2010: average, maximum, and minimum air temperature; average, maximum, and minimum soil temperature at 10 cm and average, maximum, and minimum soil temperature at 30 cm.	22
10	STEMS 2 climate data from 2006 to January 2010: average, maximum, and minimum air temperature; average, maximum, and minimum soil temperature at 10 cm; and average, maximum, and minimum soil temperature at 30 cm.	23
11	Transmittance of above-canopy light derived from photosynthetic photon flux density averaged over the growing season for GS10 light gap at STEMS 1 and HU10 light gap at STEMS 2.	24
12	Soil moisture deficit period or the fraction of growing-season days where soil water potential at 10 cm exceeded 1.0 MPa at 3, 6, 12, and 21 m into the light study gap and into the forest from each north and south edge: GS10 at STEMS 1 for 2004–2010, and HU10 at STEMS 2 for 2008–2010.	26
13	Volumetric water content measured at 10 cm depth from 2008 to 2010 at GS10 and HU10: south side, and north side.	27
14	Evaporative demand period for GS10 light gap at STEMS 1 for 2008–2009, and HU10 gap at STEMS 2 for 2008–2010.	29
15	Comparison of estimates of transmittance of above-canopy light for GS10 sensor posts at STEMS 1, and HU10 sensor posts at STEMS 2.	30
16	Regression analysis comparison of transmittance of above-canopy light for TASS III–TRAYci T estimates and corrected hemispherical photo estimates for all seedling locations at the GS10 light study gap at STEMS 1, and the HU10 light study gap at STEMS 2.	32
17	Comparative estimates of transmittance of above-canopy light from TASS III — TRAYci, uncorrected, and corrected hemispherical photos for selected south–north rows in the GS10 light study gap at STEMS 1.	33

18	Comparative estimates of transmittance of above-canopy light from TASS III — TRAYci, uncorrected, and corrected hemispherical photos for selected south–north rows in the HU10 light study gap at STEMS 2. . .	34
19	Seedling mortality for four conifer species planted at the two light study gaps: GS10 at STEMS 1 and HU10 at STEMS 2.	35
20	Mean stem length increment from 2003 to 2008 at the STEMS 1 light study for four conifer species planted across the gap perpendicular to the forest edge	39
21	Mean ground-level diameter increment from 2003 to 2008 at the STEMS 1 light study for four conifer species planted across the gap perpendicular to the forest edge	40
22	Mean stem volume increment from 2003 to 2008 at the STEMS 1 light study for four conifer species planted across the gap perpendicular to the forest edge	41
23	Mean crown volume increment from 2003 to 2008 at the STEMS 1 light study for four conifer species planted across the gap perpendicular to the forest edge	42
24	Mean stem length increment from 2005 to 2010 at the STEMS 2 light study for four conifer species planted across the gap perpendicular to the forest edge	44
25	Mean ground-level diameter increment from 2005 to 2010 at the STEMS 2 light study for four conifer species planted across the gap perpendicular to the forest edge	45
26	Mean stem volume increment from 2005 to 2010 at the STEMS 2 light study for four conifer species planted across the gap perpendicular to the forest edge	46
27	Mean crown volume increment from 2005 to 2010 at the STEMS 2 light study for four conifer species planted across the gap perpendicular to the forest edge	47
28	Relationship between log stem volume increment from 2003 to 2008 and average corrected transmittance of above-canopy light from hemispherical photos for four conifer species planted at the STEMS 1 light study.	53
29	Predicted relationships between stem volume increment from 2003 to 2008 and average corrected transmittance of above-canopy light from hemispherical photos at three levels of air and soil moisture stress for four conifer species at the STEMS 1 light study.	54
30	Relationship between log stem volume increment from 2005 to 2010 and average corrected transmittance of above-canopy light from hemispherical photos for four conifer species planted at the STEMS 2 light study	55
31	Predicted relationships between stem volume increment from 2005 to 2010 and average corrected transmittance of above-canopy light from hemispherical photos at three levels of air and soil moisture stress for four conifer species at the STEMS 2 light study.	56

A7.1	Partial residual plots of stem volume response of four species of conifer to averaged corrected transmittance of above-canopy light from hemispherical photos at the GS10 gap at STEMS 1.....	80
A7.2	Partial residual plots of stem volume response of four species of conifer to averaged soil moisture deficit period at the GS10 gap at STEMS 1.....	81
A7.3	Partial residual plots of stem volume response of four species of conifer to averaged evaporative demand period at the GS10 gap at STEMS 1.....	82
A7.4	Partial residual plots of stem volume response of four species of conifer to averaged corrected transmittance of above-canopy light from hemispherical photos at the HU10 gap at STEMS 2.....	83
A7.5	Partial residual plots of stem volume response of four species of conifer to averaged soil moisture deficit period at the HU10 gap at STEMS 2.....	84
A7.6	Partial residual plots of stem volume response of four species of conifer to averaged evaporative demand period at the HU10 gap at STEMS 2.....	85

Harvesting in many coastal forestry operations has changed in recent years with the introduction of cutting practices that involve smaller cutblocks and differing patterns of removal and retention of timber. The change in forest structure from large areas of even-aged regeneration to the greater complexity inherent in vertical layering and mixing of age classes and species has many advantages for forest productivity, health, and aesthetic enjoyment. However, the impacts on future forests and potential yields are uncertain. Little solid information exists to guide the way for policy, regulation, and guidelines related to partial cutting. Reduction in size of harvested openings, or retention of trees within cutover areas, changes the amount of light available to regenerating seedlings; the microclimatic effects associated with the stand edge will be proportionally greater in a number of small gaps than in a single gap of the same area because the ratio of edge to harvested area increases with decreasing opening size. This report examines the effect of light and other factors on regeneration at the north and south edges of the residual stand of trees based on research within a larger partial cutting study, the Silviculture Treatments for Ecosystem Management in the Sayward (STEMS) experiment (de Montigny 2004, 2009). STEMS is a large-scale, multi-disciplinary experiment that compares forest productivity, economics, and public perception of seven silvicultural systems, replicated at three sites in the Sayward Forest. A major emphasis of the STEMS project is the collection of growth and yield data, which can be used for modelling purposes. The light study reported on here (Forest Investment Account Project: Y071038) was conducted within the STEMS group selection treatment.

This light study examines the growth of Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) and associated species across a canopy gap of about 0.5 ha at two sites that represent the drier and wetter variants of the Coastal Western Hemlock Dry Maritime CWHxm subzone. The gaps were created as part of a group selection silvicultural system that emulates the variation in forest structure and openness that would occur naturally in this zone, with roughly even-aged fire-origin stands of about 20 ha or more within which small gaps are created due to mortality from root rot (B.C. Ministry of Forests and Ministry of Environment, Lands and Parks 1995). The openings created by multiple passes of a group selection system provide regeneration opportunities that create an uneven age structure, with trees of varying age, height, and diameter distributed patchily in a fine-grained mosaic. However, shade-intolerant species such as Douglas-fir have been shown to require gaps greater than 0.10 ha to successfully regenerate and reach the canopy in the CWH zone (Franklin and Dyrness 1973).

1.1 Background

Light is widely regarded as a major factor that affects the growth and development of individual trees that regenerate near or beneath a residual stand (Carter and Klinka 1992; Wright et al. 1998; Coates and Burton 1999; Lieffers et al. 1999). Other factors that contribute towards seedling regeneration in these environments include vapour pressure deficit, soil moisture, and soil nitrogen levels (Drever and Lertzman 2001; Spittlehouse et al. 2004; Walters et al. 2006). The change in harvesting practices from large cutblocks to smaller partial cuts has resulted in a higher proportion of regenerating trees

growing in conditions of partial shade (Smith 1986). The potential effects of lower light levels on mortality and future yields are unknown but may be predicted using models that analyze individual tree growth based on the relationship between light and growth, assuming that light is the major factor. Although several spatially explicit growth models have been developed (e.g., Mitchell 1975; Pacala et al. 1993), those that include regeneration must have the ability to predict light availability to simulate the growth of developing trees in the understorey, including in small gaps. Several spatially explicit light models that estimate light dynamics within stands have been developed (Canham 1995; Brunner 1998; Comeau, Macdonald, et al. 1998; Stadt et al. 2001; Groot 2004). Brunner's (1998) light model—TRAYCI—was constructed to operate in the Tree and Stand Simulator (TASS) II (Mitchell 1975) grid, and has now been adapted to function within the multi-canopy version of TASS—TASS III. Within TASS III, TRAYCI can characterize the light environment at any point in the simulated stand using ray tracing. The TRAYCI model has also been incorporated into other growth and yield models (e.g., MacFarlane et al. 2003). Light measurement is an essential part of the model testing process, and several techniques are available to researchers (Easter and Spies 1994; Comeau, Gendron, et al. 1998; Gendron et al. 1998, 2001; Lieffers et al. 1999; Comeau 2000). Tree growth simulation in response to varying light in TASS depends on a number of parameters, which must be adjusted based on measured data. The response of tree growth to light level has been measured using various approaches (Carter and Klinka 1992; Mailly and Kimmins 1997; Coates and Burton 1999; Drever and Lertzman 2001; York et al. 2004). Tree growth is also affected by soil moisture and temperature, and these factors often interact with the effect of light on growth (Voicu and Comeau 2006). For this study, we employed an approach similar to that of DeLong et al. (2002) and Wang et al. (1994), which used planted transects along a light gradient; this approach also provides light-growth response data over an area that is practical for stem mapping. The mapped locations of the residual overstorey and seedlings enabled the running of simulations for model testing.

1.2 Objectives

The objectives of this study were threefold:

1. to characterize the light conditions in a forest gap and compare estimates with modelled estimates
2. to characterize the growth of four conifer species with different shade tolerance in a forest gap
3. to model the response of the four shade-tolerant conifer species in response to gap light estimates

2 METHODS

2.1 Site Description

This light study was established within the group selection treatments of the STEMS study. Three STEMS replicates have been established: STEMS 1 harvested in 2001, STEMS 2 harvested in 2005, and STEMS 3 harvested in 2008 (de Montigny 2004, 2009).

The first light gap study was established in 2004 in the STEMS 1 replication located in the Snowden Demonstration Forest about 15 km west of Campbell

River on the Frog Lake Forest Service Road (Figure 1, Table 1). We refer to the STEMS 1 light study as "GS10," which represents the label of this particular group selection gap #10. The GS10 site is a 0.45-ha opening that measures about 50 x 90 m. In 2001, the residual stand was mainly Douglas-fir, with some western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) and western redcedar (*Thuja plicata* Donn.) (Figure 2). The residual overstorey had a height of approximately 25 m, and the terrain is relatively flat with a 2% slope and a roughly 300° aspect. The STEMS 1 site is located within the drier subvariant Coastal Western Hemlock, Eastern Very Dry Maritime (CWHxm) biogeoclimatic variant (Pojar et al. 1987). The group selection treatment is composed of site series 01 (Hwfd — Kindbergia) or 05 (Cw — Sword fern), with 5–10 cm moder humus over relatively shallow (30–60 cm) Ortho Humo-ferric Podzols with a sandy loam texture and a coarse fragment content of 35–60%. The site has a soil moisture regime of 3–4 (submesic–mesic), a soil nutrient regime of C (medium), and a site index of 31–34 (Douglas-fir) (de Montigny 2004).



FIGURE 1. Location of STEMS study sites on eastern Vancouver Island.

TABLE 1. Map co-ordinates of the light study gaps and associated climate stations

Study site	Installation type	Latitude	Longitude	Elevation (m)
STEMS 1	Climate station	50°04'05.0"	125°25'54.0"	210
	Gap—GS10	50°04'19.0"	125°25'53.0"	240
STEMS 2	Climate station	50°17'27.0"	125°26'45.0"	110
	Gap—HU10	50°19'05.3"	125°29'22.4"	190
STEMS 3	Climate station	50°04'05.1"	125°34'47.5"	340
	Gap—PP10	50°04'45.0"	125°34'13.0"	290



FIGURE 2 *Light study gaps before planting: (top) STEMS 1 (GS10) in 2004 and (centre) STEMS 2 (HU10) in 2006, viewed from the northeast corner; and (bottom) STEMS 3 (PP10) in 2009, viewed from the eastern edge.*

The second light gap study was planted in 2006 in the group selection treatment of the STEMS 2 replication located about 40 km north of Campbell River near Elk Bay on eastern Vancouver Island (Figure 1, Table 1). We refer to the STEMS 2 light study as "HU10," which represents the label of this particular harvest unit #10. The HU10 site is a roughly rectangular 0.43-ha unit with a residual stand height of 25–40 m, a slope of ~20%, and an aspect of 25° (Figure 2). The elevation is approximately 190 m. This site is quite different from the STEMS 1 site; stand composition is 75% western hemlock and 21% Douglas-fir, with some western redcedar, grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), and red alder (*Alnus rubra* Bong.). The STEMS 2 site is located within the wetter subvariant of the Coastal Western Hemlock Very Dry Maritime (CWHxm2) biogeoclimatic variant. HU10 is within site series 05 (Cw – Sword fern), with 30 cm mor-moder humus over a relatively deep (60+ cm) Ortho Ferro-humic Podzol with a loamy texture and a coarse fragment content of 15–35%. The site has a soil moisture regime of 4 (mesic), a soil nutrient regime of D (rich), and a site index of 33 and 37 for western hemlock and Douglas-fir, respectively (de Montigny 2009).

The third light gap study was planted in 2009 in the STEMS 3 replication at Gray Lake, located about 20 km west of Campbell River (Figure 1, Table 1). We refer to the STEMS 3 light study as "PP10," which is the label derived from the nickname "Peter's Pocket" that was given to this particular gap by the area forester. The PP10 site is a 0.5-ha rectangular gap surrounded by stand with a height of approximately 30 m, a slope of ~10%, and an aspect of 0° (Figure 2). The stand composition is similar to that of STEMS 1, with 15% western hemlock, 67% Douglas-fir, 15% western redcedar, and some grand fir, red alder, and western white pine (*Pinus monticola* Dougl.). The STEMS 3 site is located within the CWHxm2 biogeoclimatic variant, and the gap is predominantly site series 05. Soil moisture and nutrient regime, soil characteristics, and site index are not available for this site at this time.

2.2 Experimental Design and Site Layout

The three gaps were selected because they have roughly the same orientation and are midway between a gap of 0.1 ha and 1 ha. The light environment in a gap of 0.1 ha or less (less than one tree length) is expected to be similar to that of a forest regime, whereas in a 1-ha gap (more than four tree lengths), more than 75% of the area has a light regime similar to that above the canopy (Spittlehouse et al. 2004). The overall experimental design is essentially a randomized block design with site as the block and replication within blocks and single-species rows as the replicates. The following four coniferous species were selected to represent a range of shade tolerances:

- western white pine
- Douglas-fir
- western redcedar
- western hemlock

Each site consisted of 24 approximately north–northeast–oriented single species rows located at right angles to the southern and northern edges. The 24 rows were divided into six groups of four rows, and each species was randomly assigned to a row position within each row group. This arrangement was adopted to minimize the confounding effect on species response of any east–west moisture gradients.

2.2.1 Planting at GS10, HU10, and PP10 Species stock type information is presented in Appendix 1. For each gap, the planting grid was laid out with 100-m tapes before planting, and every planting spot was marked with a coloured flag that indicated the correct species. Planters were instructed to plant (if possible) on the flag. If poor or impossible planting spots were encountered, planters were instructed to move not more than 10 cm north or south and 30 cm east or west of the flag. After planting, seedlings were labelled with a numbered aluminum tag. The first two digits of the number designated the row; the second two digits designated the position across the gap (north-south) from the south side (i.e., Row 1 would be 101-179, Row 24 would be 2401-2479). Numbering began in the southeast corner of the planting area. For seedlings added in 2005, a preceding number "2" was added to the tag to designate the second planting year.

In 2004, seedlings were planted in the GS10 gap (STEMS 1) at a between- and within-row spacing of 3 m (to retain the option for an eventual operational spacing) over a 70 m wide area that was centred east-west across the gap and extended into the forest on the north and south edges. The within-row planting distance was reduced to 1 m approximately 20 m from the south edge and 10 m into the forest, and 10 m on each side of the north forest edge. The number of trees planted in these zones was increased to capture the rapid change in light level close to the edge of the residual stand. Because of high mortality of the western hemlock seedlings in the forest understorey due to low soil moisture, all western hemlock rows were completely replanted in 2005, and both plantings were retained for a complete season with the intention of removing one or the other based on the outcome. Although we suspected that there was a problem with stock quality, this was probably not the case because survival of the second planting was also poor. Instead of removing the first planting, we decided to remove the second planting where the original tree was still living. Tag numbers were preceded by a "2" for the remaining fill trees. A fence was installed around the planting area to exclude elk and deer, which are resident in the area.

In February 2006, a similar planting design was applied at the HU10 gap (STEMS 2) for the same conifer species (Appendix 1). The only differences in the layout were in the numbers of seedlings planted and the distance into the forest on the north side. Instead of reducing the planting distance to 1 m just at the edges, the 1-m spacing was retained across the open part of the gap in the north-south orientation. The 3-m spacing was retained throughout in the east-west direction. Budgetary limitations precluded building a fence at this site, but an ungulate deterrent, Plantskydd® (Tree World Plant Care Products Inc.) was sprayed on the seedlings every 3-4 months.

In April 2009, a similar design and identical numbering system was applied at the PP10 gap (i.e., STEMS 3). The planting grid was identical to that in the STEMS 2 gap except for one fewer E-W row in the forest on the south side and a gap between the second and third S-N rows. An access road on the south side created a "hole" in the edge shade, which necessitated the relocation of two rows east to maintain uniform shade for all rows. The planting area was fenced to exclude elk and deer browsing.

It was not possible to obtain the same seedlots of western hemlock, Douglas-fir, and white pine for planting at HU10 as for the other gaps, and the available seedlings also had differences in genetic gain for Douglas-fir and western hemlock.

At the HU10 and PP10 gaps, it was necessary to clear away large woody debris in order to have a sufficient number of plantable spots to achieve the strict planting grid.

2.3 Light Modelling

2.3.1 Light modelling using the Spot Light Interceptance Model In the process of conducting this study, growing-season fractional transmission of photosynthetic photon flux density (PPFD) or transmittance of above-canopy light (T) in the GS10 and HU10 gaps¹ was estimated using a combination of direct measurements and model estimates. The direct method involved making continuous measurements of solar radiation using quantum sensors (see Section 2.4.1). The sensors were located at points across the gaps that were selected to provide a profile of light levels in a roughly north-south orientation but at a limited number of locations. The T for each planted seedling location was estimated from hemispherical canopy photographs that were cross-calibrated against locations paired with quantum sensors. Regression analysis was used to examine relationships between data from the quantum sensors and uncorrected hemispherical photo estimates. The regression model was then used to calculate corrected T from the hemiphot data for every seedling location (Section 2.4.1). The Spot Light Interceptance Model (SLIM) (www.for.gov.bc.ca/hre/StandDevMod/LiteSlim) developed by Comeau et al. (2002) was used to calculate percent transmission of PPFD from gap fraction derived from digital hemispherical canopy images. The T derived in this way is similar to Canham's Gap Light Index (Canham 1988). The model uses known relationships between diffuse and direct light (Spitters et al. 1986), measured above-canopy PPFD, amount and distribution of canopy elements, and sun position to create sky brightness charts for the required period of estimation. The purpose of this methodology was to arrive at the best estimate of T for each planted seedling location so that the growth response could be effectively compared.

SLIM is part of a light modelling suite of programs that includes LITE, a tool for estimating light penetration through tree canopies. SLIM is a utility for processing light measurements for input into LITE (i.e., using hemispherical canopy photos or input from a quantum sensor [Plant Canopy Analyzer; LI-COR, Lincoln, Nebr.]), but it is also a stand-alone utility for producing point T estimates directly from hemispherical canopy photographs. In this study, we used the corrected T output from SLIM to pair with seedling growth measures. We also used corrected T for comparison with estimates of T from the TASS light model.

2.3.2 Light modelling using TRAYCI The light model TRAYCI (Brunner 1998) has been incorporated into TASS III as part of an effort to simulate tree growth in multi-layered stands. We were interested in comparing simulated T from TASS III/TRAYCI with our best estimates using quantum sensors and hemispherical canopy photographs, and thus validating the current version of TASS III to model light at our seedling locations. By using mapped tree co-ordinates, and data on tree height, crown length, and diameter of the unharvested mature trees (residuals) around the gap, TASS III was able to recreate the stand, and by using the light model TRAYCI and appropriate settings (Appendix 2), it was able to estimate growing-season T for all mapped seedling locations and sensor post locations. The GS10 data set was modified

¹ Funding restrictions prevented light estimates at the PP10 gap.

to add tree co-ordinates from the outer edges on the east and west sides of the gap in order to increase the depth of the mapped residual trees. This modification was considered to be justified because the stand is continuous with the mapped residual trees. Existing residual trees were assigned new co-ordinates to occupy the desired positions.

Corrected hemispherical photo T estimates were then compared with simulated TASS III estimates. From these comparisons, some generalizations regarding the accuracy of the light model in TASS III were possible.

Stem mapping The GS10 gap was stem mapped in 2005 (Figure 3) and HU10 was mapped in 2007; however, PP10 was not stem mapped. Stem mapping included every residual stem (mature tree) within at least 30 m of the edge seedlings. For GS10, the mapped residual trees consisted of 807 Douglas-fir, 116 western hemlock, 18 red alder, two Sitka spruce (*Picea sitchensis* (Bong.) Carr.), two amabilis fir (*Abies amabilis* (Dougl. ex Loud.) Dougl. ex Forbes), and one western white pine. For HU10, the mapped residual trees consisted of 1467 western hemlock, 171 Douglas-fir, 11 western redcedar, two amabilis fir, two Sitka spruce, one lodgepole pine (*Pinus contorta* Engelm. ex S. Wats.), and one western white pine. A subsample of trees from the major constituent

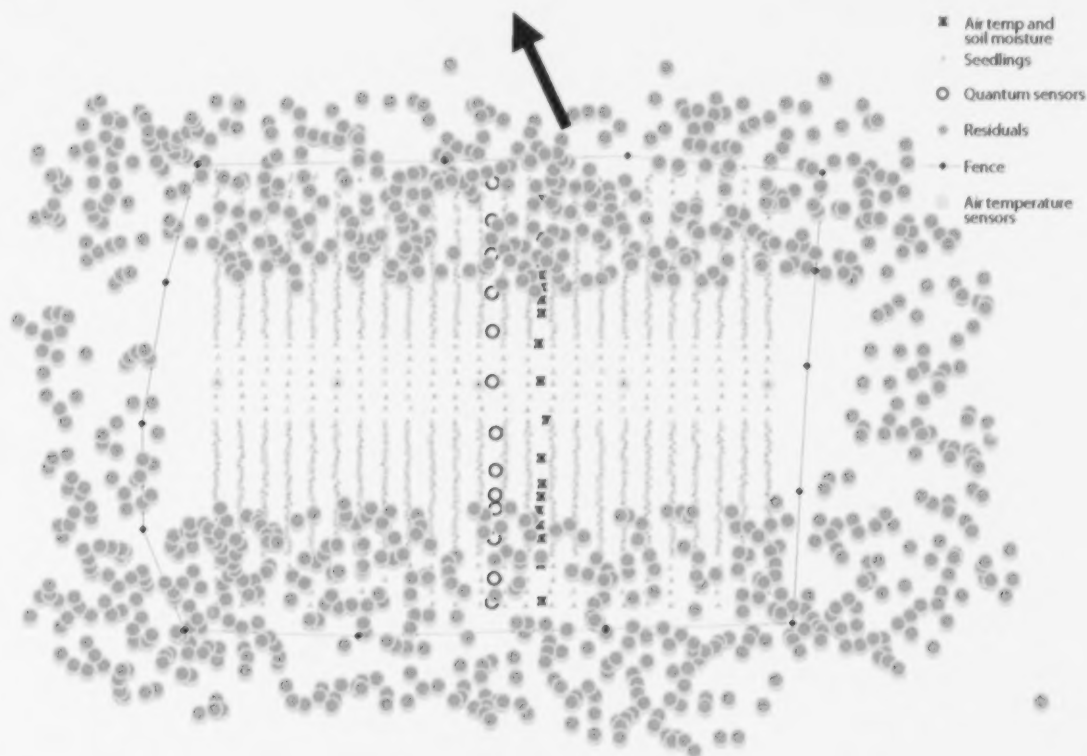


FIGURE 3 Light study gap showing mapped locations of residual trees, planted seedlings, quantum sensors, and soil moisture sensors at STEMS 1 (GS10). The arrow indicates north. The seedling rows were numbered 1–24 from east to west. Air temperature sensors on the east–west transect were located at the north–south mid-point on rows 1, 6, 12, 18, and 24 (gray dots).

species was selected for measurement of heights and crown heights for the major constituent species (Table 2). Sample trees were selected predominantly at the gap edges, and up to ~15% of the total number of trees for any one species was measured. Allometric models for estimating tree heights and crown heights from diameter at breast height (dbh) for all trees at each site were developed using the *NLIN* procedure in SAS (SAS Institute 2004) for a selected equation (Temesgen and Gadow 2004) (Table 2). Data from GS10 and HU10 were suitable for deriving equations for individual species, except for the uncommon ones where equations for the most common species were used.

Not all seedling locations were mapped. Selected seedling rows were mapped, and sufficient seedling locations were mapped to calculate the location of the intermediate seedlings. Mapping was conducted using a Nikon total station.

TABLE 2. Predicting missing height and crown height (m) values from breast height diameter for all numbered residual trees at GS10 and HU10. Equation, $y = 1.3 + a(1 - e^{bD^c})$. Independent variable (D) = diameter at breast height (cm). Dependent variable = y.

Site	Species	Dep. Var. (y)	N	a	b	c	R ²	RMSE	P value
GS10	Douglas-fir	Height	152	56.43 (22.08)	0.09 (0.05)	0.59 (0.13)	0.77	2.35	<0.0001
		Crown height	146	36.63 (40.05)	0.02 (0.01)	0.89 (0.27)	0.49	3.03	<0.0001
	Western hemlock ^a	Height	19	31.42 (1.33)	0.005 (0.002)	1.71 (0.15)	0.98	1.39	<0.0001
		Crown height	19	25.29 (1.36)	0.0008 (0.0009)	2.34 (0.39)	0.93	2.55	<0.0001
HU10	Douglas fir	Height ^b	-	-	-	-	-	-	-
		Crown height ^c	30	24.1 (1.23)	0.02 (0.05)	1.43 (0.75)	0.31	2.83	<0.0001
	Western hemlock	Height	187	35.85 (0.81)	0.02 (0.005)	1.32 (0.087)	0.85	2.66	<0.0001
		Crown height	187	20.00 (0.49)	0.01 (0.01)	1.59 (0.27)	0.39	3.26	<0.0001

a. The equations for western hemlock were used to calculate height and crown height for minor species at GS10.

b. For Douglas-fir and other minor species at HU10, equations for western hemlock were used for the calculation of height.

c. The crown height equation for Douglas-fir was used to calculate crown height for other minor species at HU10.

2.4 Climate and Microclimate Measurements

Light transmission through the canopy (T) was determined for the growing season from April 1 to October 31. For soil and air moisture stress, the period of interest was from approximately the end of June to October 31. Data acquisition and storage was achieved using CR10X data loggers (Campbell Scientific [Canada] Corp., Edmonton, Alta.). Sensors were connected for measurement using AM16/32 (soil moisture and quantum sensors) and AMT25 (thermocouples) multiplexers. To collect all data, each gap required one CR10X data logger, four AM16/32 multiplexers, and one AMT25 multiplexer. The connection of RF401 radios (Campbell Scientific [Canada] Corp., Edmonton, Alta.) to the CR10X data loggers enabled data from Snowden Demonstration Forest (GS10) and Elk Bay (HU10) communication mast base stations to be relayed via cellular phone links back to the Victoria office using LoggerNet (Campbell Scientific [Canada] Corp., Edmonton, Alta.). In February 2011, a communications mast was installed at Gray Lake to monitor site light, temperature, and rainfall. No microclimate monitoring equipment was installed at PP10.

2.4.1 Light measurement

Continuous light measurements

Light data at GS10 and HU10 have been collected hourly since the summer of 2004 and 2006, respectively, using a combination of quantum sensors (LI-190SA, LI-COR Inc., Lincoln, Nebr.) and gallium arsenide phosphide photovoltaic cells (Fielder and Comeau 2000) (Figure 4). Continuous light measurement at GS10 was discontinued in November 2010.

In both gaps, 13 quantum sensors arranged north-south across each gap were installed on steel posts with leveling fixtures (Figures 3 and 4). The post locations extended into the forest as far as the last seedling locations on the north and south sides. At GS10, the posts were spaced at 0, 9, 16, 22, 25, 31, 40, 52, 64, 73, 82, 90, and 99 m from the first seedling on the south side between rows 12 and 13 from an east-west perspective (Figure 3). The forest edges were at 22 m for the south and 73 m for the north. At HU10, the posts were spaced at 0, 9, 16, 22, 25, 31, 40, 48, 59, 68, 75, 85, and 96 m from the first seedling on the south side. The forest edges were at 22 m for the south and 68 m for the north.

Quantum sensors were connected to a CR10X data logger (Campbell Scientific [Canada] Corp., Edmonton, Alta.). Sensors were scanned at 5-s or 10-s intervals, and hourly averages were stored. Light data were collected as PPFD in units of $\mu\text{moles}/(\text{m}^2 \cdot \text{s}^{-1})$. Above-canopy measurements were made at the same time (Figure 5) at a location near each gap. At STEMS 1, three quantum sensors were positioned about 500 m away from the GS10 gap, 19 m above the ground in the clearcut treatment so that the sensors had a field of view to within 8° of horizontal. At STEMS 2, two quantum sensors were positioned on a 10-m mast about 4 km from the HU10 gap and with a similar field of view as the STEMS 1 sensors.



FIGURE 4 A custom-made quantum sensor employing a gallium arsenide phosphide photovoltaic cell (left); a line of quantum sensor posts, looking north (centre); and an individual proprietary quantum sensor on a post with levelling plate (right).



FIGURE 5 STEMS 2 communications mast (left), main climate station in HU10 gap (centre), and interior of the main enclosure (right).

Correction of quantum sensor data using calibrations Both custom-built and proprietary quantum sensors, which employ various types of photovoltaic cells, tend to become unstable after repeated, extended exposure to moist conditions (Fielder and Comeau 2000). These and other environmental assaults cause the signal response to deviate from the last calibration. This deviation may or may not self-correct when conditions dry out. Several times during the year, all quantum sensors at STEMS 1 (mast and GS10) and STEMS 2 (mast and HU10) were calibrated against a check sensor, which is compared to a standard light source (i.e., the Radiation Calibrator LI-1800, LI-COR, Lincoln, Nebr.). The frequency of calibrations during the growing season varied from once every 3 months to about once per month, with higher frequency in the last 3 years. These data were used to adjust the raw data as a daily increment based on a percentage increase or decrease in the sensor signal response as determined by the latest calibration. Using Proc GLIMMIX in SAS (SAS Institute 2004), we were able to fit smoothed functions through the calibration data for the period of sensor deployment, and the smoothed predicted values were used to adjust the raw data. The nature of the smoothed line was determined by the unique properties of a particular sensor and its response to field conditions. Sensors that consistently deviated from the original calibration by more than about 8% during the growing season were replaced. From the corrected quantum sensor measurements, daily flux was calculated (moles/m^2 per day) and then summed over the growing season to calculate the seasonal light flux. The light environment in the gaps was also expressed as the transmittance of above-canopy light (T) by dividing the sum of the below-canopy by above-canopy PPFD values for the period from April 1 to October 31.

Growing-season light estimates with hemispherical canopy photos

Seasonal estimates of light transmission (T) and PPFD at 1.5 m height for each seedling position were obtained from hemispherical canopy photographs taken at the GS10 and HU10 gaps. We used a Nikon® Coolpix 5400 camera

and FC-E9 lens with a 190° field of view, which was set to "Programmed" (P), Best Shot, Normal, 1024 × 780, fish-eye lens. Hemispherical canopy photos were analyzed using the SLIM software developed by Comeau et al. (2002), which provided hourly above-canopy PPFD (GS10 and HU10 masts), and output summaries of growing-season T and PPFD for every seedling location. Analysis of about 4000 digital images and calculation of the growing-season light estimate images at both sites was made possible by automatic thresholding algorithms in the SLIM software, which allowed batch-loading of large numbers of images for quick analysis. We used the algorithm developed by Nobis and Hinziker (2005) to analyze the images.

Correction of hemispherical canopy photo estimates with sensor data

Hemispherical canopy photo estimates of growing-season T are affected by sources of error related to characteristics of the camera, the camera settings, canopy variation, sky conditions, and light model type and assumptions (Chen et al. 1991; Frazer et al. 2001). The hourly PPFD² data collected at the 13 sensor posts were assumed to be the best estimates possible of understory light conditions. SAS (SAS Institute 2004) software was used to fit multiple regression models that related sensor T as the dependent variables to T provided by SLIM, with the inclusion of sensor position (DIST) as a second variable (Table 3). Sensor position was found to be significant in the models.

These equations were applied to SLIM output for each photo to provide corrected values of T. This was considered to be the best achievable estimate of light transmission at all the seedling locations.

TABLE 3. Equations derived from the relationship between quantum sensor and hemispherical estimates of transmitted above-canopy light (T) for the 13 sensor points at both GS10 and HU10 gaps^a

Study site	Dependent variable	Equation
GS10	Corrected T	$-0.18051 + 0.97154 \times (\text{raw hemispherical T})$ $+ 0.00942 \times (\text{DIST}) - 0.00009471 \times (\text{DIST} \times \text{DIST})$
HU10	Corrected T	$-0.11649 + 1.19009 \times (\text{raw hemispherical T})$ $+ 0.00109 \times (\text{DIST}) - 0.00002208 \times (\text{DIST} \times \text{DIST})$

^a T = the ratio of the summed below-canopy PPFD to the summed above-canopy PPFD from April 1st to October 31st; DIST = the distance (m) across the seedling grid from south to north along the quantum sensor transect.

2.4.2 Other microclimate measurements

Mast locations Air temperature probes were installed at 180 cm at the STEMS 1 mast location in 2008, but previous temperature data (2004–2008) had been collected in the centre of the GS10 gap. Air temperature measurement at the STEMS 2 and STEMS 3 mast locations commenced in 2006 and 2010, respectively (Figure 5). In 2008 at STEMS 1 and 2, and in 2010 at STEMS 3, soil temperature sensors were installed at depths of 10 cm and 30 cm at the mast locations. Relative humidity and wind sensors were installed at STEMS 2 in 2006 and at STEMS 3 in 2010. Relative humidity sensors were installed in a central location in the GS10 gap, but not at the STEMS 1 mast location until 2011. No wind monitoring equipment was installed at STEMS 1.

² PPFD = the total of the daily total PPFD (moles/[m² × s⁻¹]) from April 1st to October 31st.

As of December 2012, no sensors had been installed at the PP10 gap location (Gray Lake).

Soil moisture Gypsum blocks (GB-1 Gypsum Block, Delmhorst Instrument Co., Towaco, N.J.) were installed at both the GS10 and HU10 gaps to characterize soil moisture gradients at the north and south edges of the openings.

In 2004, three gypsum blocks were installed 10 cm below the soil surface and 1 m apart at each north-south location in the GS10 gap. The blocks were installed at the edge and at 3, 6, 12, and 21 m into the GS10 gap and into the forest from each north and south edge, and were located in a neighbouring row to the quantum sensors (Figure 3). In total, 54 gypsum blocks were installed. In 2007, all gypsum blocks were replaced at GS10 and the configuration was changed: two of the blocks were replaced at the 10 cm depth, but the third was buried at a 30 cm depth. In addition, one Echo 5 probe (Decagon Devices Inc., Pullman, Wash.) was installed at a 10 cm depth at each block location to record soil water content.

In 2007, gypsum blocks and Echo 5 probes were installed at the HU10 gap in a configuration identical to that used in GS10; monitoring commenced in 2008. Figure 6 shows some block locations at HU10 marked by air temperature sensors. Moisture block data were summarized as the soil moisture deficit period (SMDP)—the number of days during which soil water potential (SWP) exceeded 1.0 MPa as a proportion of total number of days over a 151-day period starting in early June. Soils generally remained moist until early June and were subject to drying until late-September–October.

Rainfall At STEMS 1, a tipping bucket rain gauge (Sierra-Misco Environment Ltd.) was installed at GS10 in 2004. At STEMS 2, a rain gauge (TE525MM, Campbell Scientific [Canada] Corp., Edmonton, Alta.) was installed in 2006.

Air temperature and vapour pressure deficit In 2004, unshielded fine-wire thermocouples were installed at the centre of the GS10 gap at a height of 150 cm above the ground. A shielded thermistor (Campbell Scientific Corp. [Canada], Edmonton, Alta.) was also installed at the same location in 2006;



FIGURE 6 Temperature sensors under the north canopy at HU10. An individual air thermocouple with custom-made radiation shield (left). Air temperature sensors in the canopy on the north side (right) at locations 12 m (left side of right photo), 6 m and 3 m into the forest, at the edge, and 3 m into the gap (centre of right photo). The auxiliary enclosure for the moisture block multiplexer is visible (centre of the right photo).

2.5 Seedling Measurements and Growth Modelling

this device was used to provide temperature data and to correct the thermocouple data collected in 2004 and 2005. A relative humidity sensor was also installed at this time. In 2006, air temperature and relative humidity sensors were installed at a central location in the HU10 gap at a height of 150 cm.

In April 2007, shielded thermocouples were installed at 70 cm above the ground in east-west and north-south transects at both GS10 and HU10 (Figure 6). The north-south line followed the same locations as the moisture blocks, for a total of 18 sensors, nine at each edge. For the east-west line, sensors were placed at five equidistant locations and were installed centrally at seedling rows 1, 6, 12, 18, and 24 (Figure 3). Vapour pressure deficit (VPD) was calculated using the collected relative humidity and temperature data. Data were summarized as the evaporative demand period (EDP) or the number of hours of VPD greater than 2 kPa during the growing season. For both sites, EDP was calculated for days 197–224 in 2008 and days 146–224 in 2009; for the HU10 gap, the 2010 growing season included days 146–216.

At GS10, seedling measurements were made at planting and every fall (or winter) from 2004 to 2008, and in 2010. At HU10, these measurements were made from 2006 to 2010; at PP10, they were made in 2010 and 2011. At planting, only height and diameter was recorded. Thereafter, measurements of height (also stem length for western hemlock), ground-level diameter, crown height, and crown diameter were recorded along with several condition and damage codes (Appendix 3). Fill trees planted in 2005 were not included in the analysis. Stem volume (in cubic centimetres) was calculated as a cone from ground-level diameter (gld) and height (vht):

$$\text{Stem volume} = (1/3) \times (3.1416 \times [(gld/10)/2]^2 \times [(vht/10)/2]) \times vht$$

Crown volume (in cubic centimetres) was calculated as a cone from crown length and crown area:

$$\text{Crown volume} = (1/3) \times \text{crown area} \times \text{crown length}$$

Where crown area was calculated as the sum of the four direction segments, each calculated as a quarter ellipse.

Regression analysis was used to examine relationships between cumulative stem volume increment over the first 5 years for each tree species and average transmittance for the first 5 years after planting. Stem volume increment was transformed as the natural log of the sum of the yearly increments for stem volume; light transmission was the integrated growing-season T value for each location over the number of years of growth at each seedling location (5 years). Data for SMDP and EDP were also averaged over multiple years (if available) to obtain an averaged growing-season value for the 5 years of growth. T was determined at each seedling location using hemispherical photography (see Section 2.3, Light Modelling). A nonparametric model was used to predict soil moisture values at all locations where seedlings were planted, since soil moisture was measured only along the centre row in the north-south direction. This model was a knot-based approximation to a thin plate smoothing spline and was fitted using Proc Glimmix in SAS (SAS Institute 2004). A similar smoothing spline was used to predict VPD at all seedling locations, since VPD was measured only along the centre rows in

the north-south and east-west directions. A generalized additive model (Hastie and Tibshirani 1990) was used to examine the relationship between stem volume increment and T , EDP , and $SMDP$ for each species (see Appendix 4 for SAS code example). The model fit EDP and $SMDP$ as linear terms and T as a (nonparametric) cubic smoothing spline. All terms are additive and have the following form (Wood 2006):

$$\log(y_i) = \beta_0 + \beta_1 SMDP_i + \beta_2 EDP_i + \beta_3 T_i + f(T_i) + \epsilon_i$$

where y_i is the stem volume increment on the i^{th} seedling location, $SMDP_i$ is the soil moisture deficit period, EDP_i is the evaporative demand period, T_i is the light transmittance, and $f(T_i)$ represents the remaining basis functions in the cubic smoothing spline for T_i . The residual errors ϵ_{ij} were assumed to be independent and normally distributed.

Partial residual plots were used to determine the additive contribution of terms in the model. For example, a partial residual plot for T displays T on the x axis and the additive contribution (to the generalized additive model) of T on the y axis. The functional forms represent the effect of each independent variable on stem volume increment, given the presence of all other variables in the model (Appendix 7).

2.6 Data Recording and Storage

Data were collected and stored using various electronic devices, procedures, and file types (Appendix 5). All data are stored on a government server that holds the experimental plot records of the former Research Branch, B.C. Ministry of Forests, Lands and Natural Resource Operations.

3 RESULTS

3.1 Climate

3.1.1 Photosynthetic photon flux density Figure 7a shows the PPFD (moles/m² per day) for years 2004–2009 at the STEMS 1 mast; Figure 8a shows the same for years 2006–2009 at the STEMS 2 mast. Measurements represent an average of two to four quantum sensors at STEMS 1 and two quantum sensors at STEMS 2. Radiation levels at both masts varied according to the time of day and cloud cover in summer but tended to reach a maximum of ~63 moles/m² per day at STEMS 1 and 62 moles/m² per day at STEMS 2. With cloud cover, summer minima were ~10 moles/m² per day at STEMS 1 and between 5 and 10 moles/m² per day at STEMS 2. In winter, PPFD was less than 1 moles/m² per day at both masts. Table 4 shows the annual and growing-season PPFD measured at both locations. Although growing-season totals varied according to the amount of cloud cover, they constituted approximately 85% of the annual total at both STEMS 1 and STEMS 2. At STEMS 1, the highest total growing-season PPFD was in 2004 (7412 moles/m²) and lowest in 2007 (6312 moles/m²). At STEMS 2, the highest was in 2006 (7398 moles/m²) and lowest in 2007 (6419 moles/m²). At both sites, winter data were incomplete in some years due to sensor failure and removal for repairs.

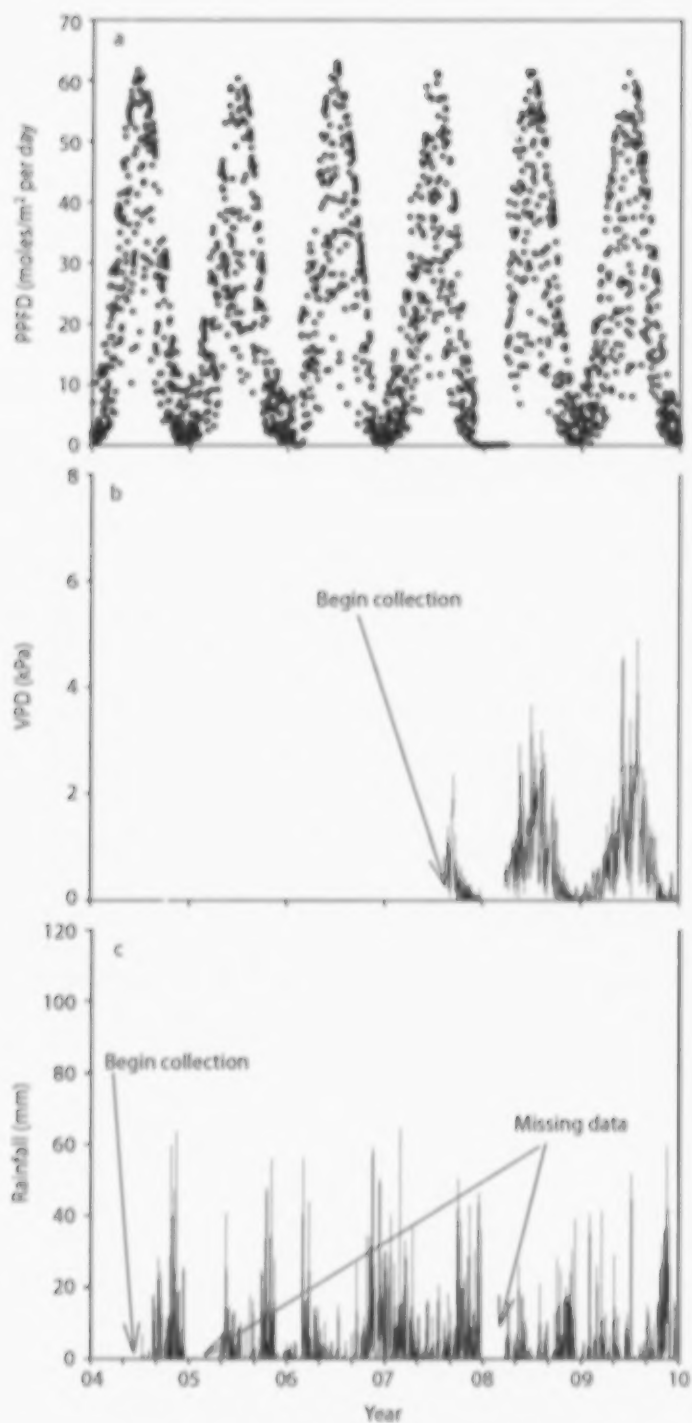


FIGURE 7 STEMS 1 mast climate data from 2004 to January 2009: (a) daily photosynthetic photon flux density (PPFD; moles/m² per day); (b) daily vapour pressure deficit (VPD; since 2008); and (c) daily rainfall (mm). "Date" markers reference January 1 of each measurement year.

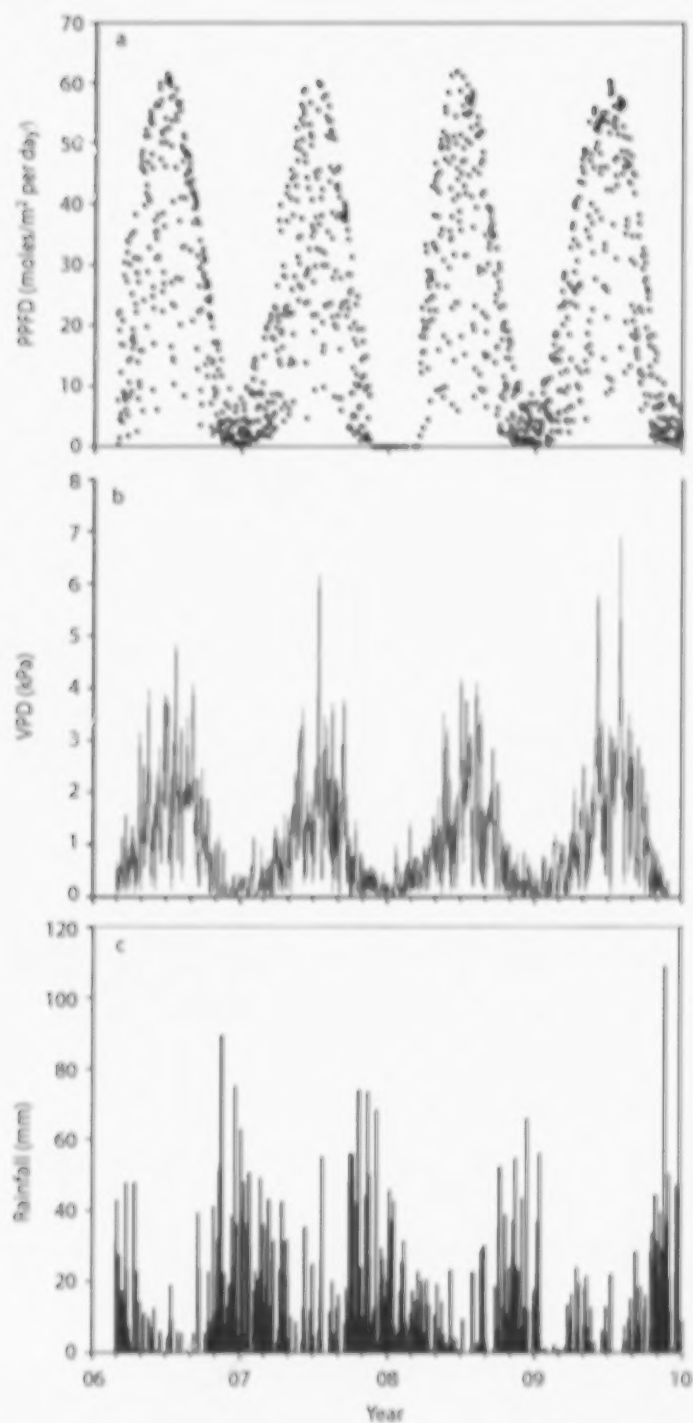


FIGURE 8 STEMS 2 mast climate data from 2006 to January 2010: (a) daily photosynthetic photon flux density (PPFD; moles/m² per day); (b) daily vapour pressure deficit (VPD); and (c) daily rainfall (mm). "Date" markers reference January 1 of each measurement year.

TABLE 4 Annual and growing-season (April 1–October 31) sums of photosynthetic photon flux density (PPFD) and rainfall for years 2004–2009 at STEMS 1 and 2006–2010 at STEMS 2. The PPFD values are sums of daily totals (mols/m² per day). Annual PPFD summaries were incomplete in 2006, 2007, and 2008 because monitoring was interrupted during the winter months.

Year	PPFD (mols/m ²)				Rainfall (mm)			
	Growing season		Annual		Growing season		Annual	
	STEMS 1	STEMS 2	STEMS 1	STEMS 2	STEMS 1	STEMS 2	STEMS 1	STEMS 2
2004	7412	—	8530	—	470	—	1385 ^a	—
2005	6624	—	7987	—	813	—	1486 ^a	—
2006	7398	7398	incomplete	—	339	482	1705 ^a	2114
2007	6312	6419	incomplete	—	768	1276	1886	3032
2008	6903	6862	incomplete	—	485	704	1195 ^a	1919
2009	6789	7123	8120	8352	573	758	1326	1850 ^a
2010	—	6638	—	7661	—	947	—	2482

a Gaps in rainfall monitoring due to equipment failure were filled using data from nearby climate stations (see Section 3.1.3).

3.1.2 Vapour pressure deficit Figure 7b shows daily maximum VPD for years 2008–2010 at the STEMS 1 mast; Figure 8b shows the same for years 2006–2009 at the STEMS 2 mast. Beginning in 2008, VPD was calculated for the centre of the GS10 gap until a relative humidity sensor was installed at the STEMS 1 mast location in 2011. Tables 5 and 6 show data summaries for annual and growing-season VPD at STEMS 1 and STEMS 2, respectively. At STEMS 1, the mean of monthly averages for the 2008 and 2009 growing seasons was 0.4 and 0.5, respectively, with mean maxima of 1.0 and 1.2, and extreme maxima of 3.7 and 4.9. At STEMS 2, the mean of monthly averages was lowest in 2007 (0.4) and highest in 2009 (0.6), with a highest mean maximum in 2009 (1.6), and a highest extreme maximum in 2009 (6.9).

3.1.3 Rainfall Figure 7c shows daily total rainfall for spring 2004 to winter 2009 at the STEMS 1 mast; Figure 8c shows the same for spring 2006 to winter 2009 at the STEMS 2 mast. At STEMS 1, most rain fell between October and March, with daily maxima reaching 60–70 mm per day. At STEMS 2, most rain fell between October and February, with daily maxima reaching more than 100 mm.

Table 4 shows total growing-season and annual rainfall (excluding snow) at both locations. To obtain a complete record for these data summaries, gaps in monitoring were filled by using rainfall data from nearby climate stations. At STEMS 1, Campbell River Airport data from January to July 2004 were used before a gauge was installed at GS10. In 2005, January–April data were lost when the rain gauge drain froze; this also occurred in January and February 2006. In 2008, battery failure caused a loss of all data from January to March; in this case, data from the Quinsam River Hatchery were used because airport data were not available. At STEMS 2, elk damage to the gauge in 2009 caused a gap in monitoring data from February to March. In this case, annual rainfall was estimated by using monthly data from an Environment Canada weather station at Chatham Point, B.C. (www.theweathernetwork.com/statistics/clio21480).

TABLE 5 STEMS 1 annual and growing-season data summaries for air and soil temperatures and vapour pressure deficit (2004–2009)

Year	Statistic ^a	Air temperature (°C)		Vapour pressure deficit ^b		Soil temperature (°C) ^c			
		Growing season	Annual	Growing season	Annual	10 cm		30 cm	
						Growing season	Annual	Growing season	Annual
2004	E _{max}	32.4	32.4	nd	nd	nd	nd	nd	nd
	Avg max	18.7	13.7	nd	nd	nd	nd	nd	nd
	Avg	12.8	9.2	nd	nd	nd	nd	nd	nd
	Avg min	9.4	6.3	nd	nd	nd	nd	nd	nd
	E _{min}	–3.5	–15.0	nd	nd	nd	nd	nd	nd
2005	E _{max}	30.2	30.2	nd	nd	nd	nd	nd	nd
	Avg max	17.2	12.4	nd	nd	nd	nd	nd	nd
	Avg	11.3	7.9	nd	nd	nd	nd	nd	nd
	Avg min	9.7	11.4	nd	nd	nd	nd	nd	nd
	E _{min}	0.2	–7.9	nd	nd	nd	nd	nd	nd
2006	E _{max}	35.2	35.2	nd	nd	nd	nd	nd	nd
	Avg max	16.5	11.3	nd	nd	nd	nd	nd	nd
	Avg	12.8	8.1	nd	nd	nd	nd	nd	nd
	Avg min	8.2	4.5	nd	nd	nd	nd	nd	nd
	E _{min}	–3.0	–13.3	nd	nd	nd	nd	nd	nd
2007	E _{max}	34.9	34.9	nd	nd	nd	nd	nd	nd
	Avg max	16.3	11.4	nd	nd	nd	nd	nd	nd
	Avg	11.7	7.8	nd	nd	nd	nd	nd	nd
	Avg min	7.8	4.7	nd	nd	nd	nd	nd	nd
	E _{min}	–3.2	–8.8	nd	nd	nd	nd	nd	nd
2008	E _{max}	30.9	30.9	3.7	3.7	inc	inc	inc	inc
	Avg max	16.6	12.1	1.0	0.8	inc	inc	inc	inc
	Avg	11.5	7.9	0.4	0.3	inc	inc	inc	inc
	Avg min	7.2	4.1	0.1	0.1	inc	inc	inc	inc
	E _{min}	–3.0	–13.0	0.0	0.0	inc	inc	inc	inc
2009	E _{max}	36.6	36.6	4.9	4.9	18.4	18.4	17.1	17.1
	Avg max	18.3	12.3	1.2	0.8	12.1	8.5	11.6	8.3
	Avg	12.7	7.9	0.5	0.3	11.7	8.2	11.4	8.2
	Avg min	8.0	4.2	0.1	0.1	11.4	7.9	11.3	8.1
	E _{min}	–1.3	–7.8	0.0	0.0	2.9	0.6	3.3	1.6

a Statistics include means of monthly averages (Avg), means of monthly maxima and minima (Avg max and Avg min), and extreme maxima and minima (E_{max} and E_{min}).

b A relative humidity sensor was installed in 2007; data are missing for years before sensor installation ("nd").

c Soil sensors were installed in 2008; data are missing for years before sensor installation ("nd") or for years with partial data collection ("inc").

TABLE 6 STEMS 2 annual and growing-season data summaries for air and soil temperatures and vapour pressure deficit (2006–2010)^a

Year	Statistic ^b	Air temperature (°C)		Vapour pressure deficit		Soil temperature (°C) ^c			
		Growing season	Annual	Growing season	Annual	10 cm		30 cm	
						Growing season	Annual	Growing season	Annual
2006	E _{max}	35.5	35.5	4.8	4.8	nd	nd	nd	nd
	Avg max	19.3	inc	1.5	1.2	nd	nd	nd	nd
	Avg	13.4	inc	0.5	0.4	nd	nd	nd	nd
	Avg min	8.8	inc	0.1	0.1	nd	nd	nd	nd
2007	E _{min}	–3.0	inc	0.0	0.0	nd	nd	nd	nd
	E _{max}	35.7	35.7	6.2	6.2	nd	nd	nd	nd
	Avg max	17.6	12.9	1.3	0.8	nd	nd	nd	nd
	Avg	12.5	8.7	0.4	0.2	nd	nd	nd	nd
	Avg min	8.4	5.4	0.1	0.0	nd	nd	nd	nd
2008	E _{min}	–1.9	–7.8	0.0	0.0	nd	nd	nd	nd
	E _{max}	31.8	31.8	4.2	4.2	21.0	inc	17.3	inc
	Avg max	17.9	13.1	1.3	0.9	16.5	inc	12.6	inc
	Avg	12.2	8.4	0.5	0.3	15.7	inc	12.2	inc
	Avg min	7.7	4.7	0.1	0.0	14.8	inc	11.9	inc
2009	E _{min}	–3.2	–11.8	0.0	0.0	8.7	inc	13.0	inc
	E _{max}	38.3	38.3	6.9	6.9	23.9	23.9	20.4	20.4
	Avg max	19.4	13.8	1.6	1.1	16.5	11.5	15.0	10.9
	Avg	13.4	8.8	0.6	0.4	15.5	10.8	14.6	10.6
	Avg min	8.5	4.9	0.1	0.1	14.6	10.2	14.4	10.4
2010	E _{min}	–1.0	–7.4	0.0	0.0	4.7	2.1	5.2	2.7
	E _{max}	35.5	35.5	6.2	6.2	22.2	22.2	19.3	19.3
	Avg max	18.9	14.2	1.4	0.9	15.6	11.9	14.5	11.4
	Avg	12.9	9.4	0.5	0.3	14.7	11.2	14.2	11.2
	Avg min	8.3	5.8	0.1	0.0	13.8	10.5	13.8	10.5
	E _{min}	–1.6	–10.7	0.0	0.0	5.7	1.6	6.7	3.7

a Note that the mast was located 4 km from the HU10 light gap. In addition, air temperature data were missing for February and March in 2006, thus yielding incomplete monthly averages for the year.

b Statistics include means of monthly averages (Avg), means of monthly maxima and minima (Avg max and Avg min), and extreme maxima and minima (E_{max} and E_{min}).

c Soil sensors were installed in 2008; data are missing for years before sensor installation ("nd") or for years with partial data collection ("inc").

At STEMS 1, total annual rainfall varied between 1195 mm in 2008 and 1886 mm in 2007. Growing-season rainfall ranged from 339 mm in 2006 to 813 mm in 2005. At STEMS 2, total annual rainfall varied between 1850 mm in 2009 and 3032 mm in 2007. Growing-season rainfall ranged from 482 mm in 2006 to 1276 mm in 2007. High-light years tend to be associated with lower rainfall, especially during the growing season. The growing seasons in 2005 and 2007 at STEMS 1 and in 2007 and 2010 at STEMS 2 were rather wet com-

pared to other years. In 2006, the winter had high rainfall but the summer was relatively dry at both locations. Similarly, the growing seasons of 2008 and 2009 had intermediate rainfall at both locations.

3.1.4 Air temperature Figure 9a shows air temperature data for spring 2004–2009 at STEMS 1; Figure 10a shows the same for spring 2006–January 2010 at STEMS 2. Tables 5 and 6 show data summaries for annual and growing-season air temperatures at STEMS 1 and STEMS 2, respectively.

At STEMS 1, mean average air temperatures varied between 7.8 and 9.2°C annually and 11.3 and 12.8°C during the growing season. Mean maximum temperatures for the growing season were highest in 2004 and lowest in 2007. Mean minimum temperatures for the growing season were highest in 2005 and lowest in 2008. Extreme maximum air temperatures ranged from 36.6°C in 2009 to 30.2°C in 2005; extreme minimum air temperatures varied between -15.0°C in 2004 and -7.8°C in 2009.

At STEMS 2, mean average air temperatures varied between 8.4 and 9.4°C annually and 12.2 and 13.4°C during the growing season. Mean maximum temperatures for the growing season were highest in 2009 and lowest in 2007. Mean minimum temperatures for the growing season were highest in 2006 and lowest in 2008. Extreme maximum air temperatures varied between 38.3°C in 2009 and 31.8°C in 2008; extreme minimum air temperatures varied between -11.8°C in 2008 and -7.4°C in 2009.

3.1.5 Soil temperature Figures 9b and 9c (STEMS 1) and 10b and 10c (STEMS 2) show soil temperature data since 2008 when sensors were installed at both mast locations. Tables 5 and 6 summarize data for annual and growing-season soil temperatures at STEMS 1 and STEMS 2, respectively. At both locations, growing-season means were generally 3°C higher than the annual means. In addition, both sites recorded growing-season soil temperatures of less than 5°C. At the 30-cm depth, soils were slightly warmer in the winter but cooler in the summer than at the 10-cm depth.

At STEMS 1, soil temperatures at the 10-cm depth never fell below 0°C in 2009. The annual average temperature was 8.2°C; the growing-season average was 11.7°C. The highest soil temperature at the 10-cm depth was 18.4°C; the lowest was 0.6°C. At the 30-cm depth, a high of 17.1°C and a low of 1.6°C were recorded.

At STEMS 2, soil temperatures at the 10-cm depth never fell below 1.6°C. Annual averages were 10.8°C in 2009 and 11.2°C in 2010; growing-season averages were 15.5°C in 2009 and 14.7°C in 2010. The highest soil temperature at the 10-cm depth was 23.9°C; the lowest was 1.6°C. At the 30-cm depth, average growing-season soil temperatures were 12.2, 14.6, and 14.2°C in 2008, 2009, and 2010, respectively; a high of 20.4°C and a low of 2.7°C were recorded in 2009.

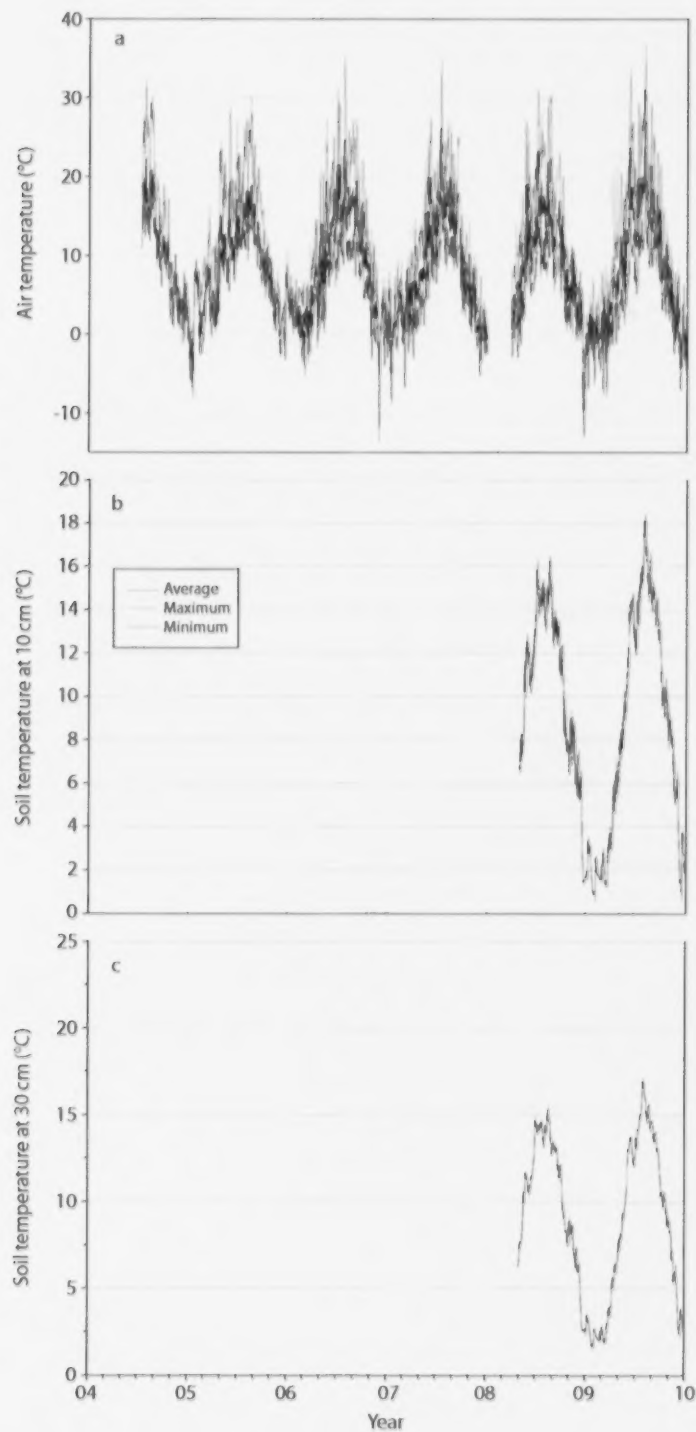


FIGURE 9 STEMS 1 climate data from 2004 to January 2010: (a) average (black), maximum (red), and minimum (blue) air temperature (since 2004); (b) average, maximum, and minimum soil temperature at 10 cm (since 2008); and (c) average, maximum, and minimum soil temperature at 30 cm (since 2008).

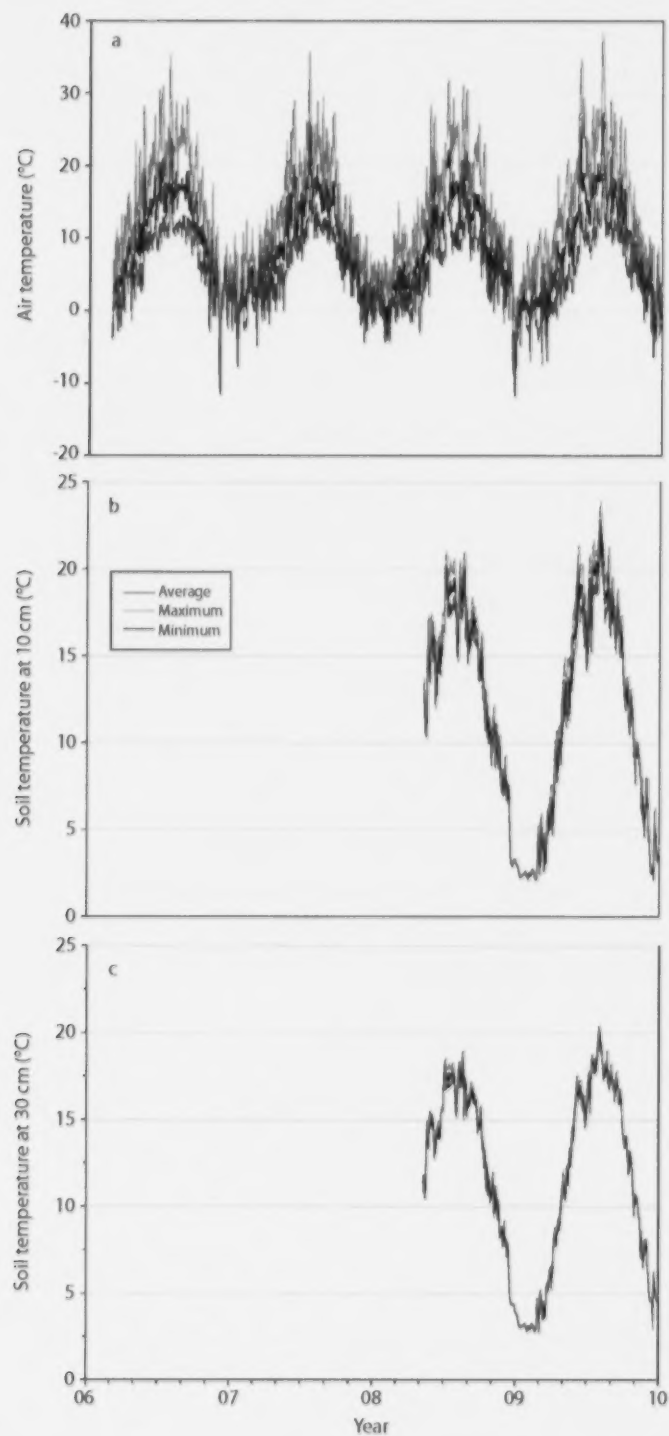


FIGURE 10 STEMS 2 climate data from 2006 to January 2010: (a) average (black), maximum (red), and minimum (blue) air temperature; (b) average, maximum, and minimum soil temperature at 10 cm (since 2008); and (c) average, maximum, and minimum soil temperature at 30 cm (since 2008).

3.2 Microclimate Monitoring

3.2.1 Light monitoring Figure 11 summarizes all light data as the transmittance of above-canopy light (T) captured by quantum sensors on north-south transects across the GS10 (STEMS 1) (2004–2010) and HU10 (STEMS 2) (2007–2010) study gaps during the growing season (April 1–October 31). Light levels in the residual stand were quite different on the north and south sides of the GS10 gap at STEMS 1 (Figure 11a). T increased from >0.1 to ~ 0.25 from 20 m into the residual stand to the stand edge on the south side, whereas the north side exhibited T values of >0.1 to 0.65 . Maximum T of ~ 0.8 occurred approximately 32 m (about one tree length) from the south edge of the 54-m gap.

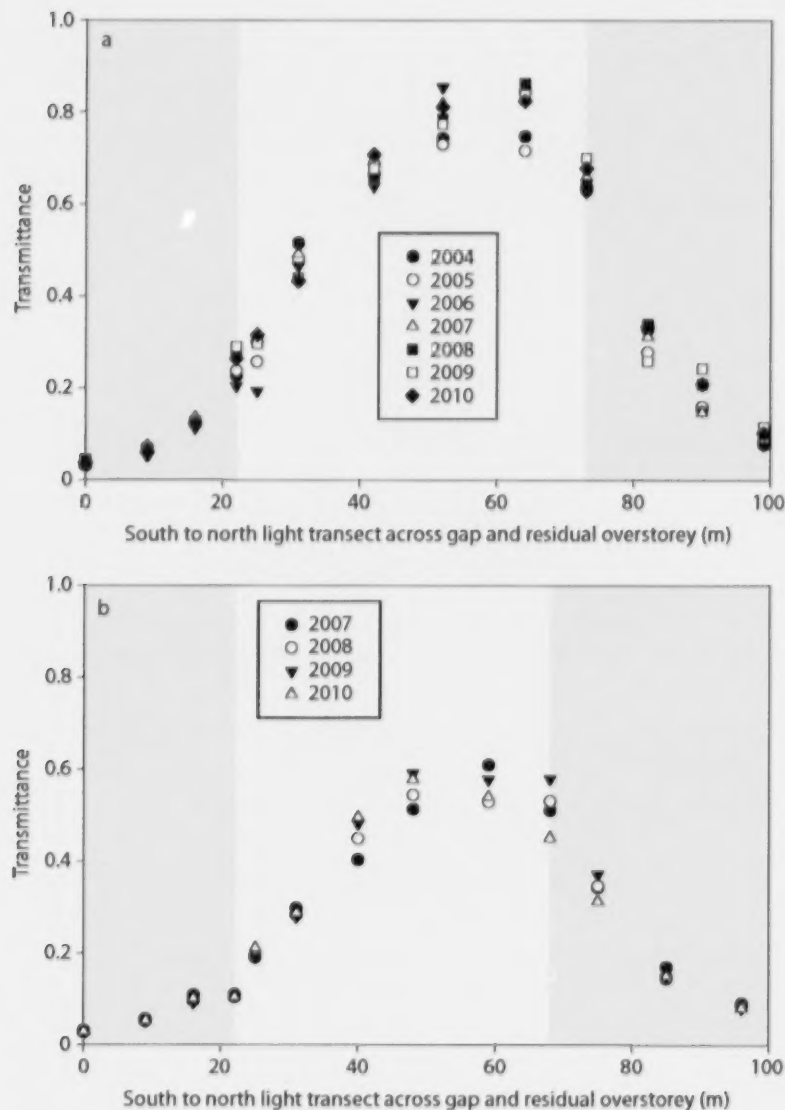


FIGURE 11 Transmittance of above-canopy light (T) derived from photosynthetic photon flux density averaged over the growing season for (a) GS10 light gap at STEMS 1 (2004–2010) and (b) HU10 light gap at STEMS 2 (2007–2010).

In the HU10 gap at STEMS 2, T increased from <0.1 to ~ 0.2 from 20 m into the residual stand to the stand edge on the south side, whereas the north side exhibited T values of >0.1 to ~ 0.5 (Figure 11b). Maximum T of ~ 0.6 occurred approximately 38 m from the south edge of the 46-m gap. Therefore, T values increased from 0.2 to ~ 0.6 over a distance of 38 m, which represents roughly one tree length.

3.2.2 Soil moisture monitoring Figure 12 shows the soil moisture deficit period at each moisture-block position north and south of the south and north edges at the GS10 and HU10 gaps.

At GS10, soils generally did not begin to dry out until June and were not consistently wet again until the rains started in September (Figure 13a). Soil drying was dramatically greater in the residual stand compared to the gap, but dropped off very quickly 3 m from the forest edge (Figure 12a). The drop-off was greater at the south edge, presumably because of reduced radiant heating, compared to the north edge. Values for 2005 were the lowest of the years monitored, which corresponded with the wetter summer months, as shown by the rainfall data (Figure 7c); values in 2006 were the highest, which corresponded with a summer of low rainfall (Figure 7c). On the north edges, soil moisture decreased in a comparable way in 2004 and 2006 (Figure 12a). However, south-side soils appeared to dry out for a longer period in 2006 than in earlier years, but they still showed a similar trend for distance from the edge. In 2006, much more drying occurred on the gap's south side than in earlier years. In addition, some soil drying occurred on the gap's north side in 2006, possibly due to increased vegetation competition, which was not present in 2005 and 2007. Salal (*Gaultheria shallon*) had been clipped in 2004, and further vegetation removal was performed in 2006 (Appendix 6); however, the general level of competition from salal and bracken fern (*Pteridium aquilinum*) had increased since planting, and clipping may have had only a short-term effect on leaf area index and water utilization by the vegetation.

At HU10, soils did not dry out enough to register SWP values greater than 1 MPa in 2008; however, understory sensors detected dry soils for part of the 2009 growing season and to a greater degree in 2010 (Figure 12b). This pattern of drying was consistent with the site's topography and hydrology. For instance, the south side, positioned at the top of a 20% slope, has a greater tendency to dry out than the north edge, which is positioned at the slope bottom and is thus prone to seepage. Therefore, the sun's drying effect on the north side is somewhat offset by these topographic factors. Little drying in the gap was evident except on the south side close to the edge.

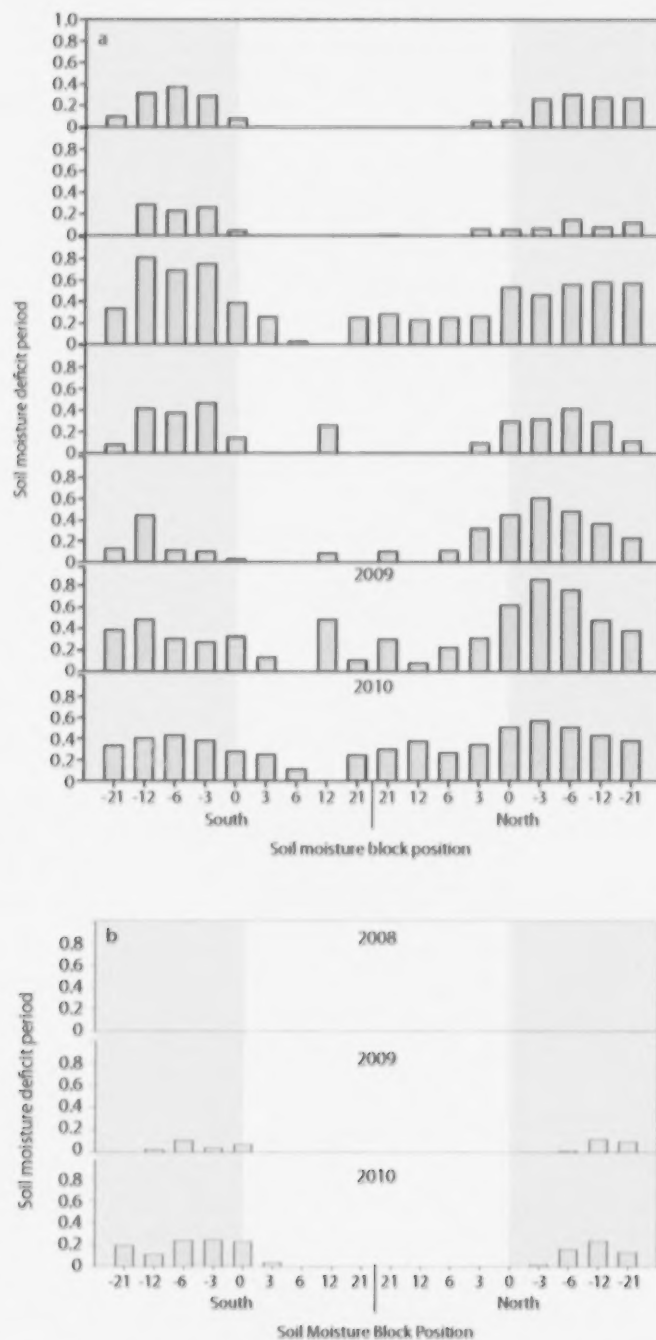


FIGURE 12 Soil moisture deficit period (SMDP) or the fraction of growing-season days (151 days) where soil water potential at 10 cm exceeded 1.0 MPa at 3, 6, 12, and 21 m into the light study gap and into the forest from each north and south edge: (a) GS10 at STEMS 1 for 2004–2010, and (b) HU10 at STEMS 2 for 2008–2010. The grey shaded areas indicate the area with residual overstorey mature tree cover.

Figure 13 shows soil volumetric water content at a 10-cm depth on the south and north sides of the GS10 (left) and HU10 (right) gaps. On both sides of these gaps, most sensor traces in the winter showed that soil water content was $0.2\text{--}0.3\text{ m}^3/\text{m}^3$ for GS10 and approximately $0.2\text{--}0.35\text{ m}^3/\text{m}^3$ for HU10, which is assumed to represent saturated soils at these sites.

At GS10, several rain events during spring 2008 produced successive peaks and drying cycles, none of which resulted in a water content of less than $\sim 0.1\text{ m}^3/\text{m}^3$ (Figure 13a, 13b [left]). The trace for the south edge (0 m) declined considerably during the winter and dried to below zero in the summer (Figure 13a [left]). Sensors at GS10 that displayed negative volumetric water content values most likely were installed close to coarse fragment content, which would have created a significant zone around the sensor in which moisture could not be retained. Although the reinstallation of the south edge sensor (and others not shown) during fall 2008 met with mixed success, some generalizations can be made. For instance, a long drying cycle was evident from early June to early August; during this period, soils were quite dry.

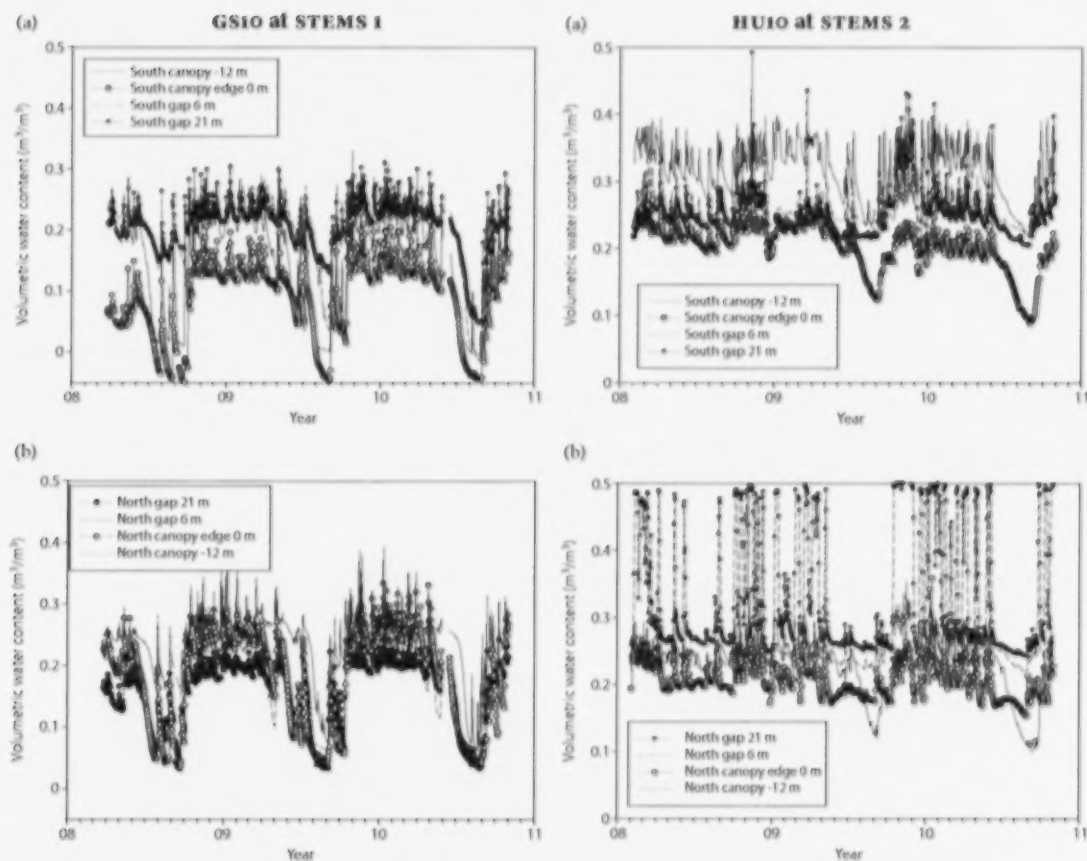


FIGURE 13 Volumetric water content measured at 10-cm depth from 2008 to 2010 at GS10 (left) and HU10 (right): (a) south side, and (b) north side. Sensors were located at 0, 3, 6, 12, and 21 m into the gap and into the forest on the south and north gap edges.

This trend was particularly evident beneath the canopy and close to the residual stand edge; within the gaps, soil moisture was highly variable. Soils remained dry except for two more wetting and drying cycles, during the summer. Soils generally became saturated again in October.

At HU10, one sensor trace 21 m into the gap at the north side (Figure 13b [right]) spiked to $0.5 \text{ m}^3/\text{m}^3$ during rain events. Frequent rain events were interspersed with drying cycles, but no trace decreased below $\sim 0.2 \text{ m}^3/\text{m}^3$ during the summer months. The frequency of rainfall and hydrological characteristics at this site keep soils relatively moist throughout the summer months. The high spikes in soil water content indicate complete saturation, which is consistent with the presence of ephemeral streams on the hillside.

3.2.3 Hourly air temperature, and calculation of vapour pressure deficit and evaporative demand period Variation in VPD across the gap may explain some of the variation in growth response that was not explained by light or SWP (Chen et al. 1993; Spittlehouse et al. 2004). Vapour pressure deficit was calculated from sensor temperature measurements and gap relative humidity. Figure 14 summarizes VPD as the evaporative demand period (EDP), or the number of hours VPD was greater than 2 kPa during the growing season. For both the GS10 and HU10 gaps, temperature measurement points were at 3, 6, 12, and 21 m either side of the forest edge on the south and north sides of the gaps.

Figure 14a shows EDP changed dramatically from the south to north edges of the GS10 gap. Under the south residual stand, the EDP was about 30 hours, and it remained low until approximately 12 m from the forest edge. It then increased rapidly to ~ 130 hours and peaked at ~ 200 hours approximately 3 m from the north edge.

Figure 14b shows EDP increased from the south to the north edges of the HU10 gap. Under the south residual stand, EDP was less than 50 hours, and it remained low until approximately 23 m from the forest edge, where it rose rapidly to ~ 100 hours and then peaked at 150 hours approximately 3 m from the north edge. At both gaps, EDP decreased in the canopy on the north side but never to levels as low as those in the south canopy locations.

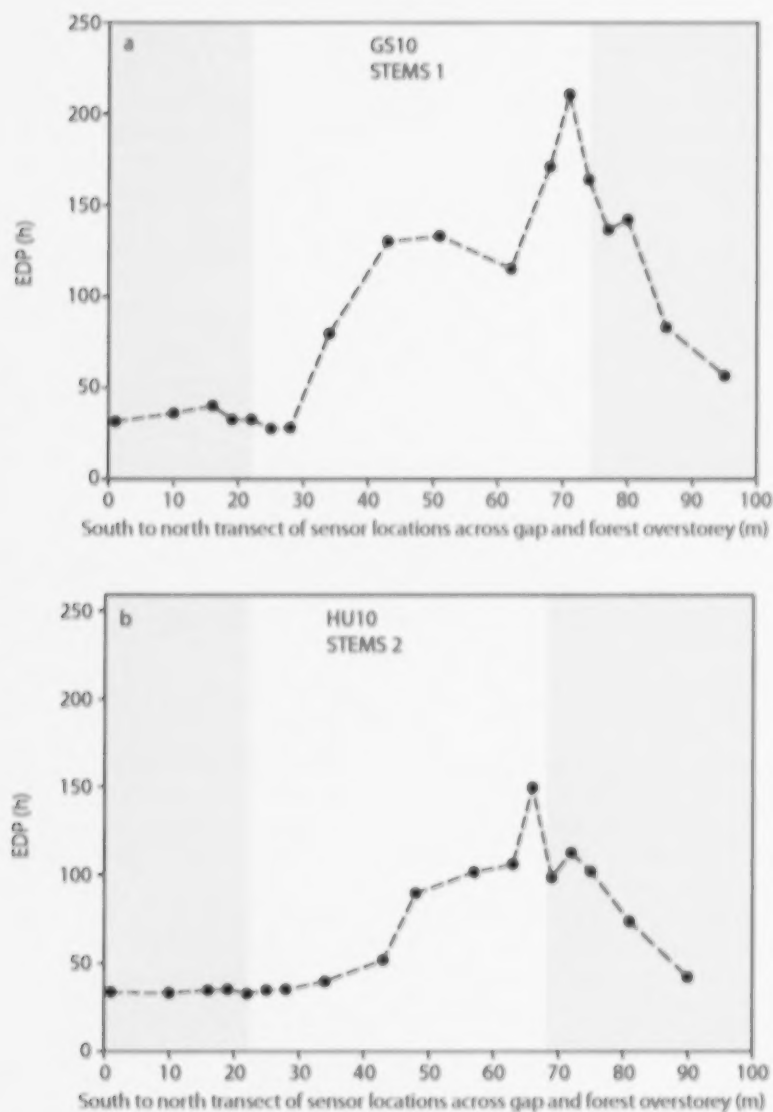


FIGURE 14 Evaporative demand period (EDP) for (a) GS10 light gap at STEMS 1 for 2008–2009, and (b) HU10 gap at STEMS 2 for 2008–2010. For both gaps, measurement points were 0, 3, 6, 12, and 21 m either side of the forest edge on the south and north sides of the gaps. For GS10, the south edge is at 22 m on the graph's X axis and the north edge is at 73 m. For HU10, the south edge is at 22 m on the graph's X axis and the north edge is at 68 m.

3.3 Estimates of Growing-season Light

3.3.1 Gap sensors and correction of hemispherical values Figure 15 provides quantum sensor and hemispherical photo T estimates at 13 quantum sensor positions in the GS10 and HU10 light study gaps. As described in Section 2.4.1, hemispherical canopy photo estimates of growing-season T are affected by several sources of error, which increase inversely with the degree of light attenuation by the canopy. We do not know the precise reason why SLIM overestimates the transmitted light in the residual overstorey, but one

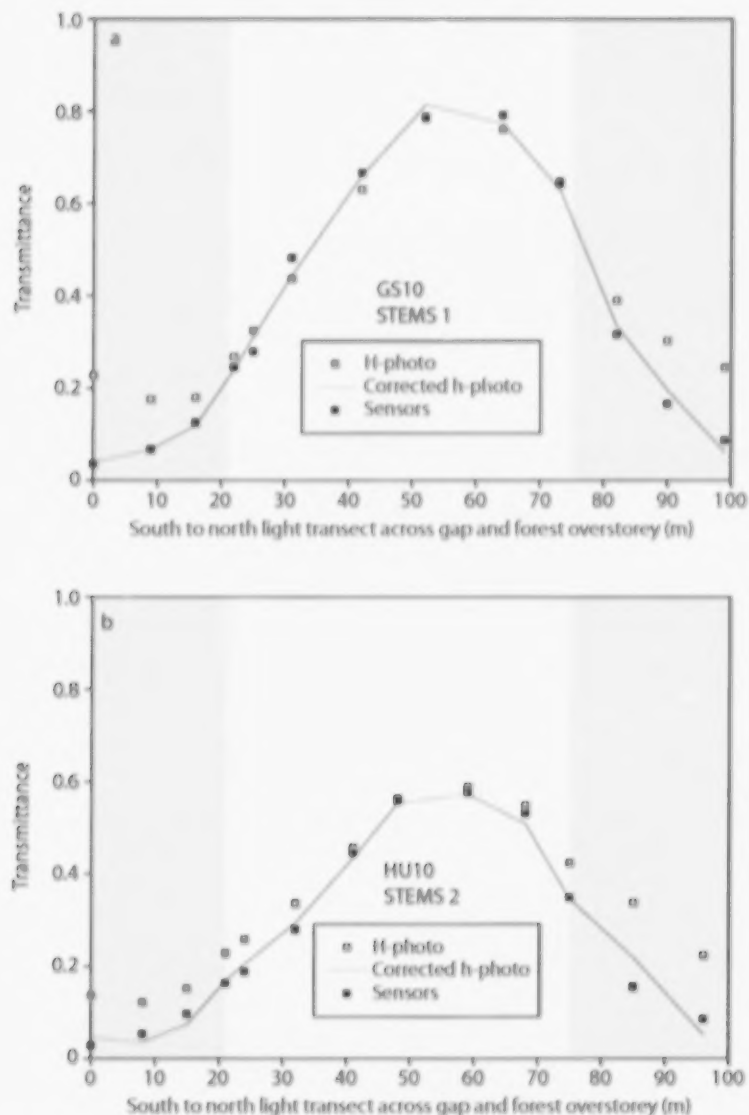


FIGURE 15 Comparison of estimates of transmittance of above-canopy light (T) for (a) GS10 sensor posts at STEMS 1, and (b) HU10 sensor posts at STEMS 2. Estimates were derived from hourly averages obtained from quantum sensors and hemispherical photos. The predicted relationship between the sensor readings and hemispherical photo estimates is also shown as "Corrected h-photo." This relationship was used to correct all other hemispherical photo estimates.

contributing factor may be errors in the estimation of canopy gaps due to photographic distortion of canopy elements and possibly the contribution of the diffuse light component. To correct the hemispherical photo estimates, equations were developed for both gaps by using regression analysis (Table 3). The final objective of light measurements was to obtain a reasonable esti-

mate of light transmission through the canopy at approximately 1.5 m above the ground at each seedling location. With successive growing seasons, seedlings will obviously have grown higher than 1.5 m; however, we assumed that this estimate will serve for the first few years of stand development. These estimates were intended to provide the main explanatory variable of seedling growth.

Comparison of *T* from corrected hemispherical photos and *trayci* For both light study gaps, a linear model fit the relationship between corrected hemispherical photo *T* estimates, derived from hemispherical photographs taken at every seedling location, and those modelled from tree lists with *trayci* operating as part of TASS III (Figure 16). For GS10, the points separate into two bands, which indicates that the relationship between the two estimation methods depends on location within the gap. This separation is greatest at lower light levels, which suggests that there was a difference in the estimation of light transmission through the canopy. For HU10 (Figure 16b), the points also separate into two bands, which indicates a similar location-dependent relationship between the two methods of estimation; however, the curve is shifted to the right of the origin, which indicates that *trayci* consistently overestimates at this site. Light profiles were plotted for selected rows in both gaps (Figures 17 and 18). Each graph shows the north-south profile at a different east-west location in the gap, and compares values from uncorrected hemispherical photographs, corrected hemispherical photo estimates, and TASS III-*trayci* estimates. For the GS10 gap, these profiles show that *trayci* tends to underestimate *T* at the east, west, and north edges, whereas agreement seems good for the south edge. Row 12 where the edge influence from east and west is the least shows the best agreement. Uncorrected hemispherical photos clearly overestimate values at low light levels under the canopy on the south and north sides. The corrected hemispherical and *trayci* curves are closer under the south canopy than the north at GS10 (Figure 17). The light profiles plotted for selected rows in the HU10 gap show that *trayci* tends to strongly overestimate the amount of light penetrating the canopy on the south edge of the gap, whereas agreement is generally good for the north edge. The *trayci* model also tends to overestimate the drop off in *T* at the gap's east and west edges (Figure 18).

Corrected *T* obtained from hemispherical photos is calculated using measured open-sky PPFD values as input, whereas *trayci* uses estimated open-sky values. Differences in the calculation of sky radiance data and amounts of diffuse and beam (direct) light might account for some of the observed differences in light profiles across the gaps.

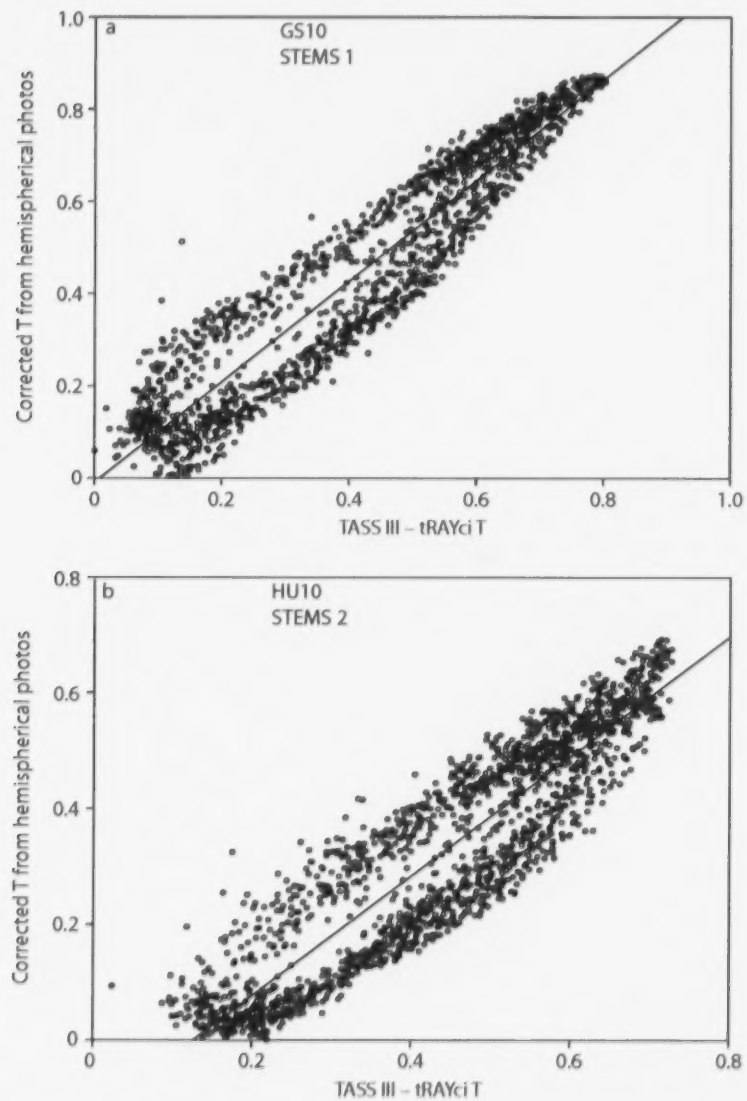


FIGURE 16 Regression analysis comparison of transmittance of above-canopy light (T) for TASS III-tRAYci T estimates and corrected hemispherical photo estimates for all seedling locations at (a) the GS10 light study gap at STEMS 1, and (b) the HU10 light study gap at STEMS 2.

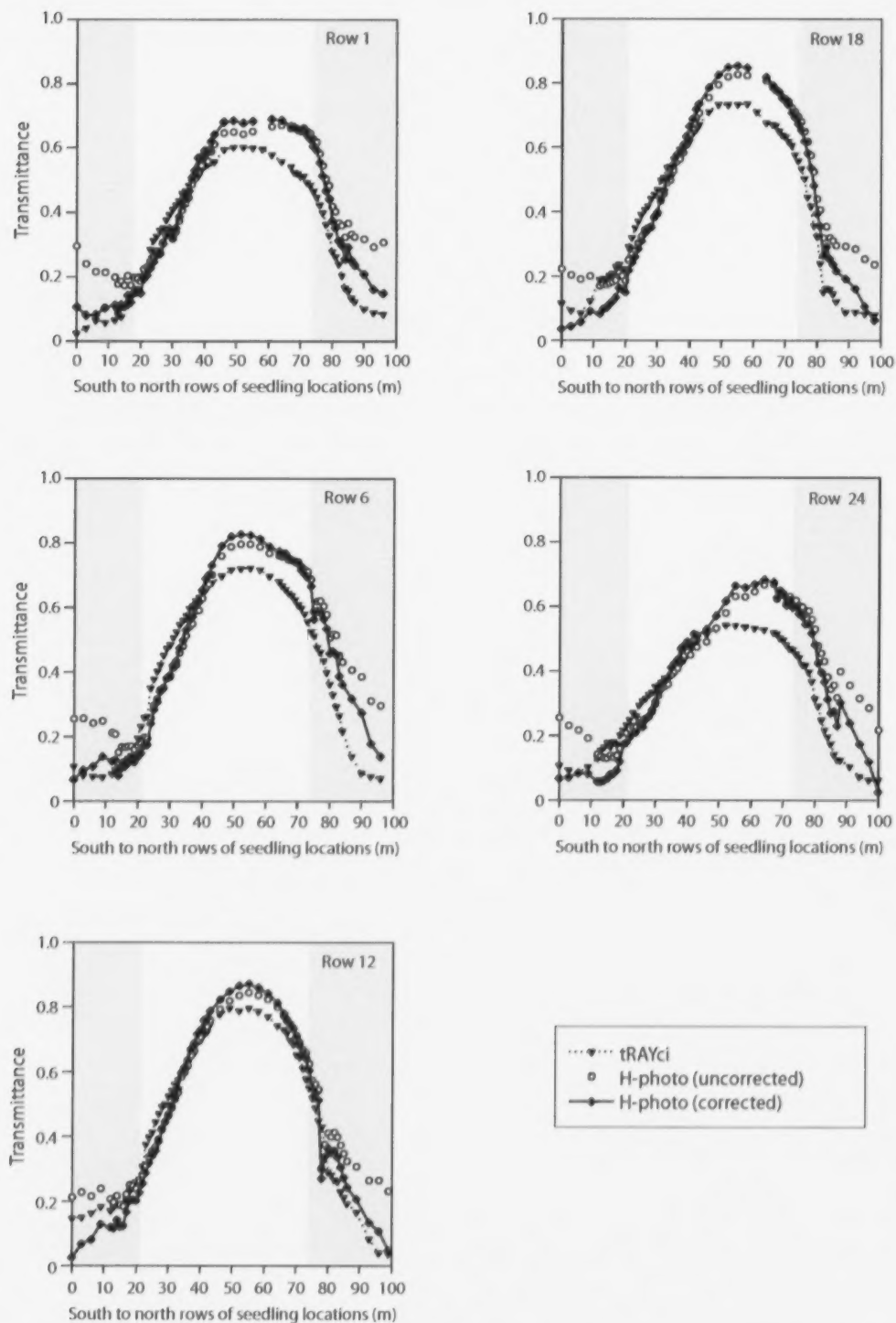


FIGURE 17 Comparative estimates of transmittance of above-canopy light from TASS III—tRAYci, uncorrected, and corrected hemispherical photos for selected south–north rows in the GS10 light study gap at STEMS 1. Grey shading represents the edge of the gap and residual forest.

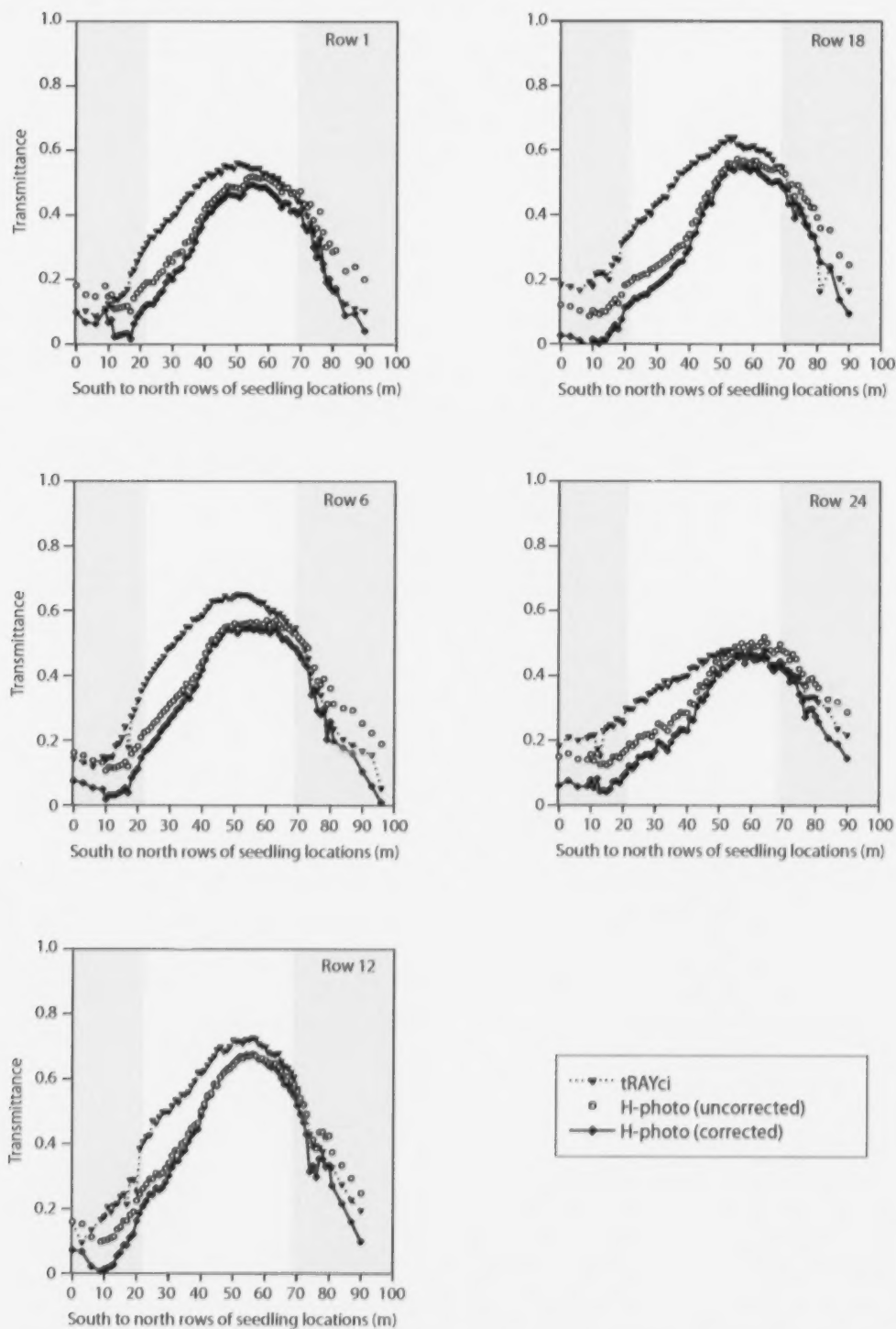


FIGURE 18 Comparative estimates of transmittance of above-canopy light from TASS III—tRAYci, uncorrected, and corrected hemispherical photos for selected south–north rows in the HU10 light study gap at STEMS 2. Grey shading represents the edge of the gap and residual forest.

3.4 Seedling Measurements

Figure 19 shows mortality for all planted seedlings at both light study gaps. Table 7 (GS10) and Table 8 (HU10) present data summaries of annual seedling growth for each species. Figures 20–23 summarize seedling growth increment (stem length, diameter, stem volume, crown volume) at the GS10 gap as the mean of north–south row position, with a row bearing of 32° and the south and north edges at 22 m and 74 m, respectively. Figures 24–27 provide the same information for HU10 seedlings, with a row bearing of 25° and the south and north edges at 22 m and 68 m, respectively. At both light study gaps, the general pattern of growth was typified by poor response under the residual stand, and improvement with distance from the stand edge to a maximum permitted for the prevailing environmental conditions.

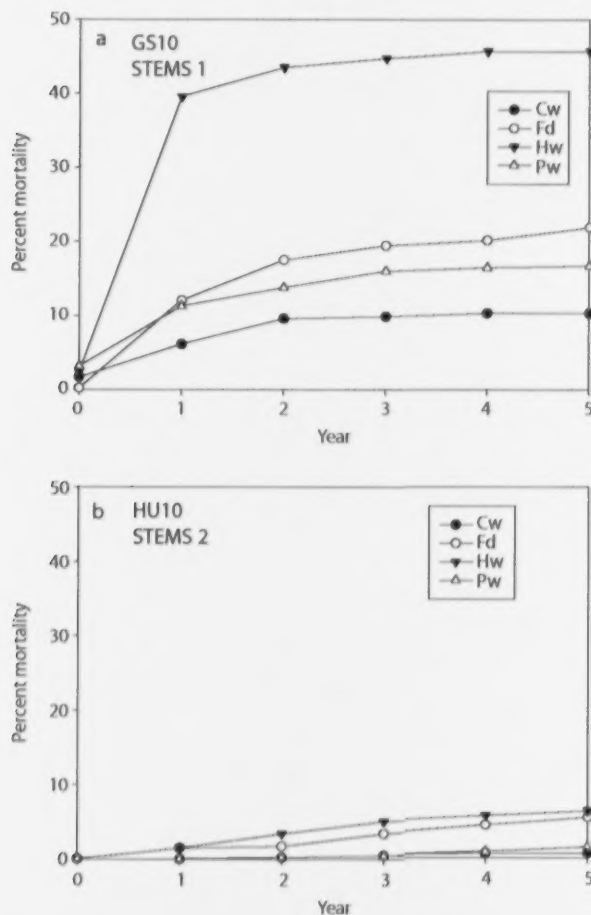


FIGURE 19 Seedling mortality for four conifer species planted at the two light study gaps: (a) GS10 at STEMS 1 (2003–2008) and (b) HU10 at STEMS 2 (2005–2010). CW: western redcedar; Fd: Douglas-fir; Hw: western hemlock; Pw: western white pine.

TABLE 7 Annual seedling growth means and standard deviations, and browsing damage for the first 5 years (2003–2008) in the GS10 light study gap at STEMS 1

Species ^a	Year ^b	Diameter (mm)	Stem length (cm)	Stem volume (cm ³)	Crown volume ^c (m ³)	Browsing damage ^d (%)
Cw	0	3.7 (0.5)	41.5 (5.6)	1.6 (0.6)		
	1	5.4 (0.9)	51.7 (8.7)	4.2 (2.1)	0.007 (0.005)	0
	2	7.8 (2.7)	72.1 (22.0)	15.2 (15.3)	0.035 (0.038)	0
	3	10.8 (4.9)	91.3 (34.4)	43.1 (48.5)	0.095 (0.115)	0
	4	13.8 (8.0)	108.9 (49.4)	103.0 (134.8)	0.219 (0.262)	0
	5	18.9 (11.6)	124.0 (63.3)	238.1 (318.1)	0.430 (0.523)	0
Fd	0	4.1 (0.6)	33.9 (4.6)	1.6 (0.5)		
	1	5.3 (0.9)	46.0 (6.7)	3.6 (1.7)	0.004 (0.002)	0
	2	7.8 (2.6)	60.1 (16.4)	12.2 (12.5)	0.011 (0.012)	0
	3	9.5 (3.9)	77.9 (28.7)	27.1 (31.3)	0.043 (0.056)	0
	4	11.7 (6.0)	88.6 (36.8)	55.1 (75.5)	0.073 (0.091)	0
	5	15.0 (8.1)	103.4 (49.0)	115.8 (173.0)	0.155 (0.219)	0
Hw	0	3.6 (0.7)	32.6 (7.1)	1.1 (0.6)		
	1	5.2 (1.1)	46.1 (11.5)	3.2 (2.0)	0.005 (0.004)	0
	2	8.1 (2.5)	79.2 (26.8)	14.6 (12.5)	0.033 (0.036)	0
	3	11.2 (4.7)	110.6 (42.5)	38.3 (40.1)	0.087 (0.088)	0
	4	14.5 (6.5)	135.3 (53.5)	105.4 (133.5)	0.235 (0.253)	0
	5	20.0 (9.0)	165.2 (66.5)	258.2 (350.9)	0.549 (0.798)	0
Pw	0	4.3 (0.7)	16.0 (4.2)	0.8 (0.4)		
	1	5.1 (1.0)	22.7 (5.8)	1.7 (0.9)	0.000 (0.000)	0
	2	7.0 (2.0)	32.0 (10.1)	5.0 (4.6)	0.002 (0.002)	0
	3	8.5 (3.2)	48.8 (19.1)	12.9 (14.7)	0.013 (0.016)	0
	4	10.3 (5.0)	58.4 (25.9)	27.3 (35.1)	0.031 (0.038)	0
	5	14.3 (7.2)	75.8 (33.4)	70.2 (93.2)	0.063 (0.073)	0

a Cw: western redcedar; Fd: Douglas-fir; Hw: western hemlock; Pw: western white pine.

b The first year's growth was in the nursery.

c Crown dimensions were not measured at planting.

d The GS10 gap was fenced, which prevented browsing.

TABLE 8 Annual seedling growth means and standard deviations for the first 5 years (2005–2010) in the HU10 light study gap at STEMS 2

Species ^a	Year ^b	Diameter (mm)	Stem length (cm)	Stem volume (cm ³)	Crown volume ^c (cm ³)	Browsing damage ^d (%)
Cw	0	3.6 (0.5)	24.9 (4.8)	0.9 (0.3)		0
	1	4.8 (1.1)	39.5 (8.3)	2.6 (1.6)	0.007 (0.005)	23
	2	6.3 (2.3)	49.2 (15.0)	6.7 (7.2)	0.021 (0.024)	5
	3	9.0 (3.6)	57.4 (18.8)	16.9 (20.5)	0.031 (0.034)	12
	4	11.4 (6.4)	66.9 (27.2)	38.4 (67.6)	0.051 (0.066)	4
	5	15.0 (8.9)	82.1 (41.0)	93.8 (136.8)	0.103 (0.139)	1
Fd	0	4.3 (0.7)	30.8 (5.5)	1.6 (0.6)		0
	1	5.4 (1.3)	43.6 (7.8)	3.6 (2.3)	0.005 (0.004)	0
	2	8.6 (3.8)	59.5 (18.7)	17.1 (22.3)	0.026 (0.029)	0
	3	12.4 (5.8)	74.2 (25.8)	46.8 (61.4)	0.066 (0.073)	8
	4	15.9 (8.7)	85.5 (33.7)	99.2 (138.5)	0.100 (0.124)	5
	5	21.1 (13.1)	106.1 (50.3)	256 (385.1)	0.256 (0.338)	0
Hw	0	3.7 (0.6)	20.8 (4.5)	0.7 (0.4)		2
	1	4.7 (1.2)	37.4 (8.4)	1.9 (1.4)	0.005 (0.003)	23
	2	7.8 (3.2)	62.3 (21.1)	11.7 (13.7)	0.035 (0.036)	1
	3	12.3 (6.2)	89.0 (37.1)	53.0 (71.1)	0.118 (0.143)	0
	4	16.8 (9.6)	113.9 (54.1)	138.5 (188.8)	0.222 (0.287)	0
	5	23.3 (14.7)	144.5 (76.5)	372.6 (548.7)	0.452 (0.615)	0
Pw	0	3.9 (0.7)	9.0 (2.2)	0.4 (0.2)		0
	1	4.3 (0.9)	13.1 (3.2)	0.7 (0.4)	0.001 (0.000)	46
	2	6.1 (2.2)	21.5 (6.9)	2.7 (2.7)	0.003 (0.003)	21
	3	9.1 (3.5)	35.7 (12.0)	10.7 (11.9)	0.009 (0.009)	1
	4	11.6 (6.0)	40.8 (16.8)	24.5 (37.4)	0.013 (0.017)	1
	5	17.0 (10.1)	57.5 (26.3)	84.8 (129.4)	0.044 (0.055)	0

a Cw: western redcedar; Fd: Douglas-fir; Hw: western hemlock; Pw: western white pine.

b The first year's growth was in the nursery.

c Crown dimensions were not measured at planting.

d The HU10 gap was not fenced.

3.4.1 Western hemlock

GS10 gap at STEMS 1 First-year mortality, presumably due to water stress, was relatively severe compared to the other three species under the residual stand on the north and south sides of the GS10 light study gap at STEMS 1. Although mortality of western hemlock seedlings was 37% in the first year after planting, it increased by only 6% over the subsequent 4 years (2005–2008) (Figure 19a). By zone, western hemlock suffered 83% mortality under the north canopy, 75% under the south canopy, and 8.4% in the gap. After 5 years, overall seedling growth means were 20 mm for ground-level diameter, 165 cm for stem length, 258 cm³ for stem volume, and 0.55 m³ for crown volume (Table 7). Mean stem length increment was 20 cm under the south canopy, increased to 50 cm at the edge and then reached a general maximum of 150 cm ~10 m from the south edge (Figure 20). Stem length increment across the gap was variable but declined rapidly ~5 m from the north edge into the north canopy. The pattern of mean ground-level diameter increment across the gap was similar, and achieved a maximum close to the south edge (Figure 21). Diameter increment was ~5–7 mm at the south canopy edge, and increased to 25 mm ~15 m from the south edge, but rapidly declined within 5 m of the north canopy edge; however, a decrease in diameter increment across the gap was not apparent. Mean stem volume increment reached a maximum (600 cm³) ~10 m from the south edge but declined rapidly ~5 m from the north edge (Figure 22). Stem volume increment was 10–20 cm³ under the canopy, 500 cm³ ~5 m from the north edge, and 100 cm³ at the edge. Mean crown volume increment was 0.05 m³ at the south edge, then increased to approximately 0.5 m³ at 5 m from the south edge and to about 1 m³ at ~10 m (Figure 23). It remained very variable across the gap, and declined rapidly into the canopy from ~0.5 m³ to 0.05 m³ over 10 m. Western hemlock can achieve maximum crown volume increment at relatively low light levels.

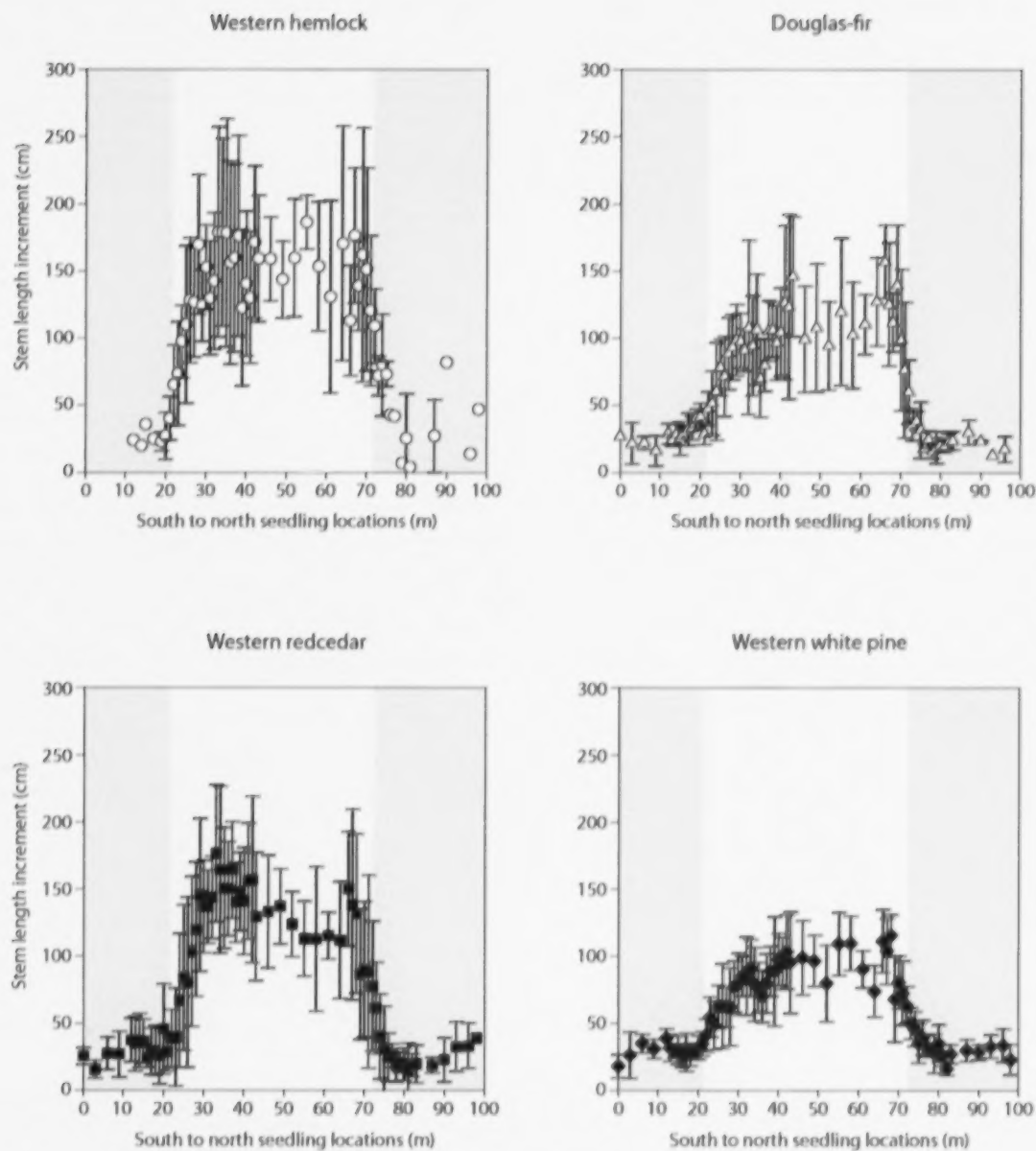


FIGURE 20 Mean stem length increment from 2003 to 2008 at the STEMS 1 light study (GS10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

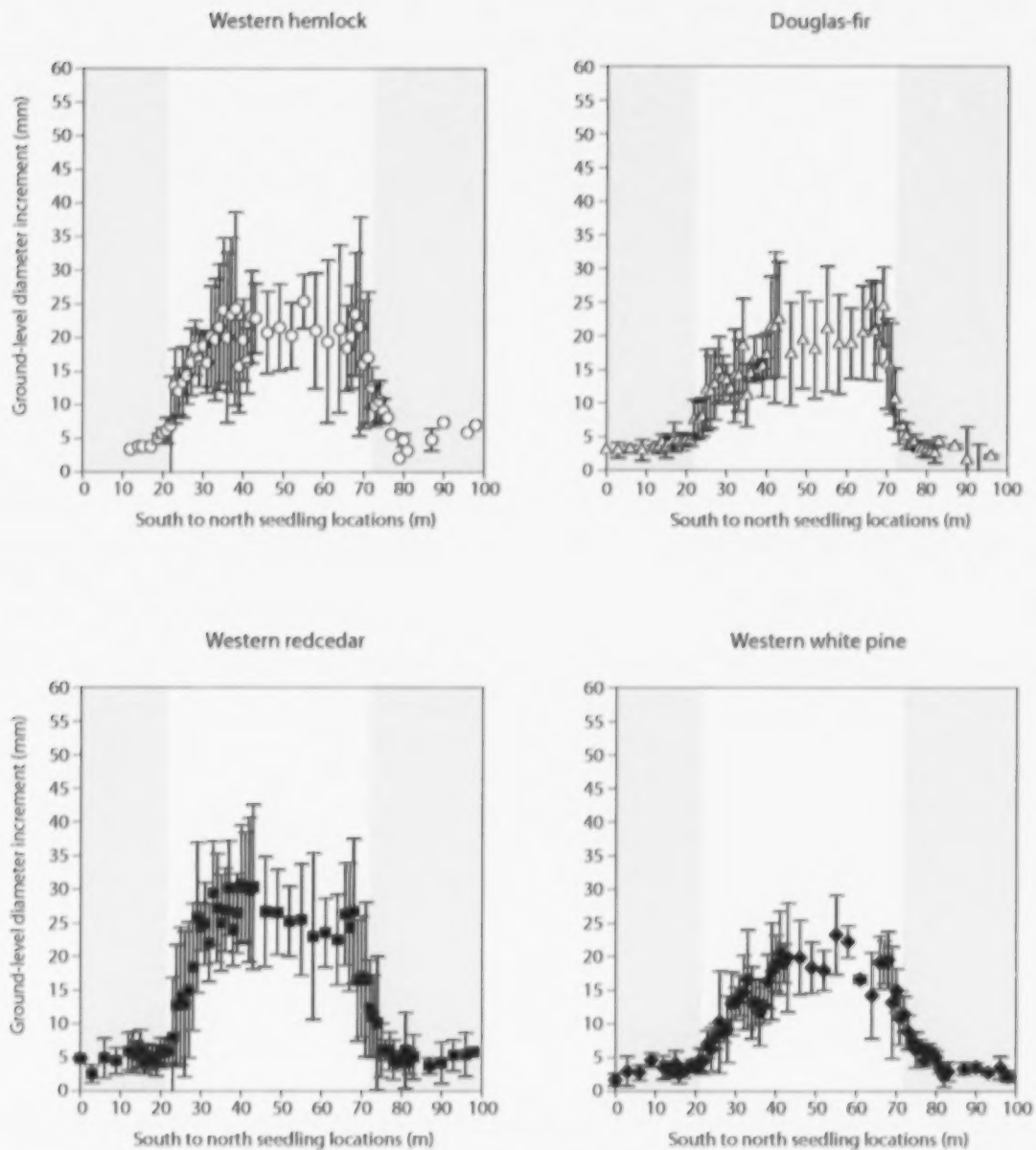


FIGURE 21 Mean ground-level diameter increment from 2003 to 2008 at the STEMS 1 light study (GS10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

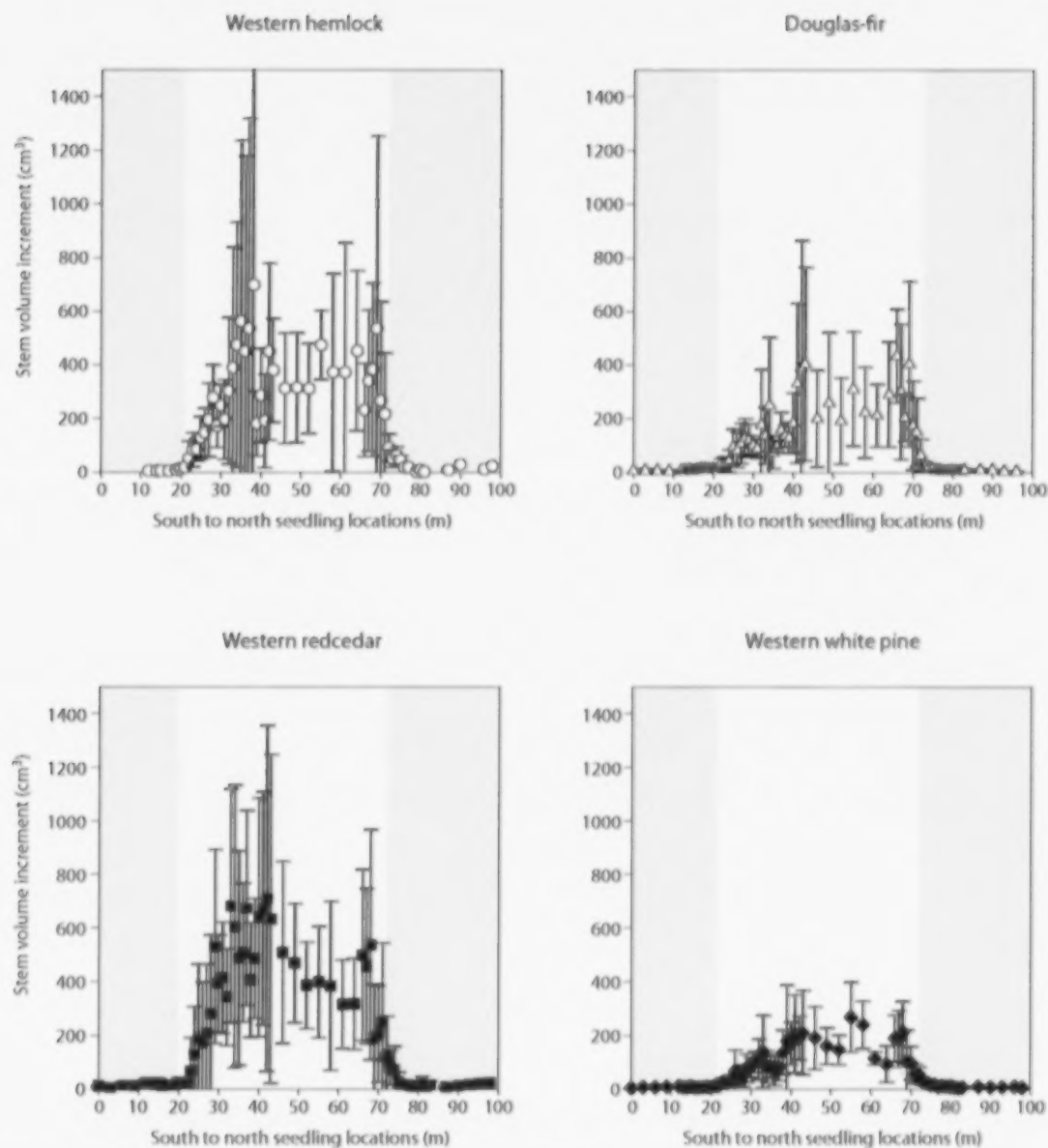


FIGURE 22 Mean stem volume increment from 2003 to 2008 at the STEMS 1 light study (GS10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

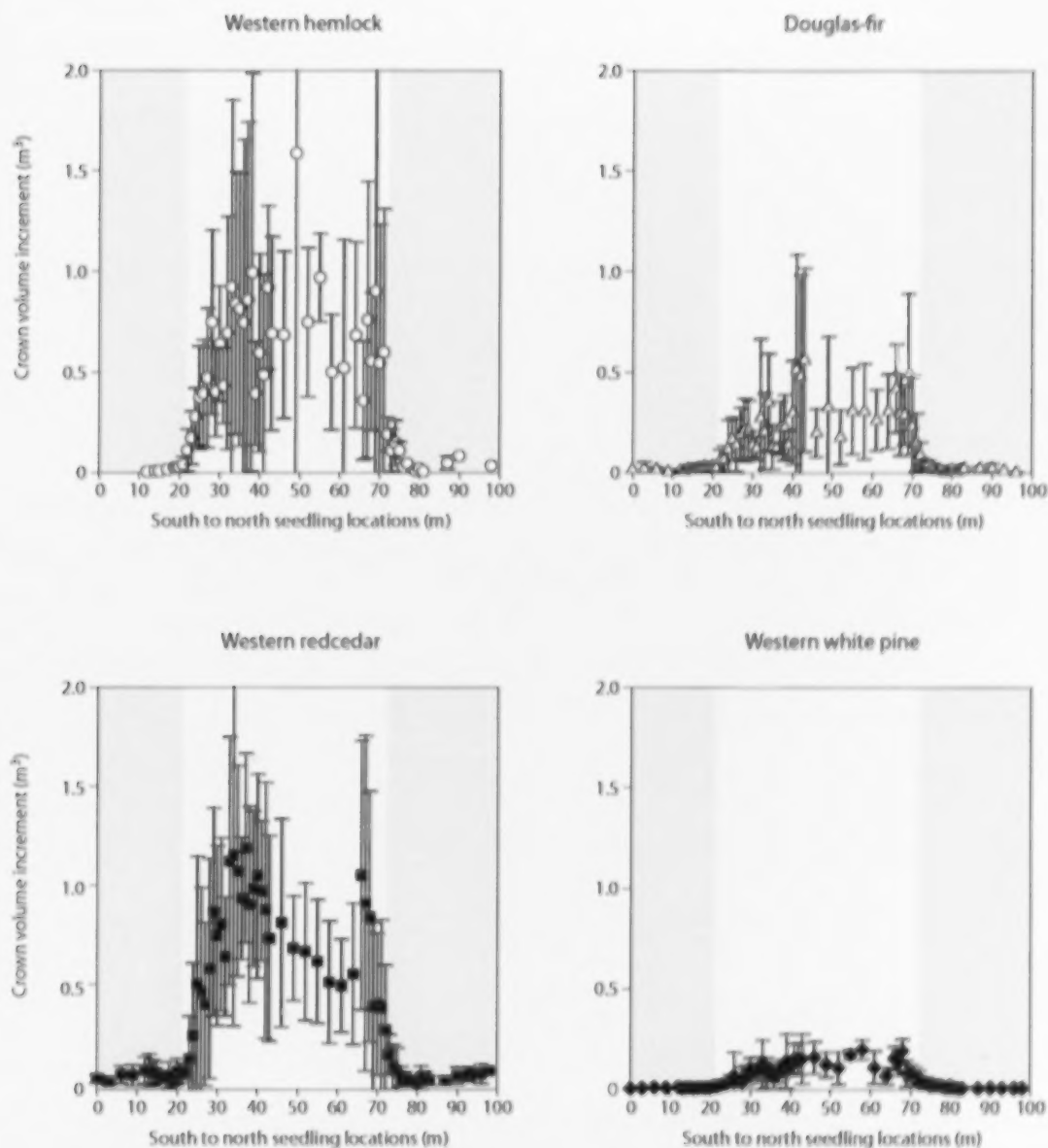


FIGURE 23 Mean crown volume increment from 2003 to 2008 at the STEMS I light study (GS10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

HU10 gap at STEMS 2 In the HU10 light study gap at STEMS 2, mortality of all western hemlock seedlings was about 6% over the 4 years after planting (Figure 19b). By planting area zone, western hemlock suffered 1.1% mortality under the north canopy, 8.1% under the south canopy, and 6.7% in the gap. After 5 years, overall seedling growth means were 23 mm for ground-level diameter, 145 cm for stem length, 373 cm³ for stem volume, and 0.45 m³ for crown volume (Table 8). Mean stem length increment was 40 cm under the south canopy, then increased to 50 cm at the edge and reached a general maximum of 200 cm ~10 m from the south edge (Figure 24). Stem length increment across the gap was variable: at the north edge, it declined to between 150 and 200 cm, and then decreased abruptly to ~100 cm within 3 m of the north edge and declined to 50 cm under the north canopy. The pattern of mean ground-level diameter increment across the gap was similar: it achieved a maximum close to the south edge (Figure 25). Diameter increment was ~3 mm under the south canopy, increased to 5 mm at the edge, and continued to increase to approximately 35 mm ~15 m from the south edge; it declined to ~25 mm at the north edge, after which values declined rapidly within the north canopy to ~5 mm. Mean stem volume increment was 2–8 cm³ under the south canopy, and increased to 13 cm³ at the edge (Figure 26). At 10 m from the south edge, stem volume increment was about ~700 cm³, after which values became increasingly variable (between 100 and 1300 cm³), and approximated 600 cm³ at the north edge. Beyond the north edge, values declined to ~50 cm³ in the first 5 m but did not fall below 20 cm³. Mean crown volume increment was 0.002–0.015 m³ under the south canopy, increased to 0.03 m³ at the south edge, achieved a maximum of 0.8 m³ ~10 m from the south edge, remained highly variable (0.15–1.7 m³) across the gap to the north edge, then declined rapidly to 0.25 m³ at the edge under the north canopy (Figure 27). At 5 m into the north canopy, crown volume increment had declined to about 0.1 m³ but never dropped below 0.02 m³. As at the GS10 gap, western hemlock was able to achieve maximum crown volume increment at relatively low light levels.

3.4.2 Western redcedar

GS10 gap at STEMS 1 In the GS10 light study gap at STEMS 1, mortality of all western redcedar seedlings was 6% in the first year after planting, increased to 8% in the second year, and then remained unchanged (Figure 19a). By planting area zone, western redcedar suffered 1.4% mortality under the north canopy, 21.5% under the south canopy, and 4.6% in the gap. After 5 years, overall seedling growth means were 19 mm for ground-level diameter, 124 cm for stem length, 238 cm³ for stem volume, and 0.43 m³ for crown volume (Table 7). Mean stem length increment was 20 cm under the south canopy, increased to 50 cm at the edge, and then reached a general maximum of 150 cm ~10 m from the south edge (Figure 20). Stem length increment tended to decrease across the gap, but ~10 m from the north edge, western redcedar seedlings had a stem length increment of 150 cm; height then declined rapidly ~5 m from the north edge into the north canopy. The pattern of mean ground-level diameter increment across the gap was similar: it achieved a maximum close to the south edge (Figure 21). Diameter increment

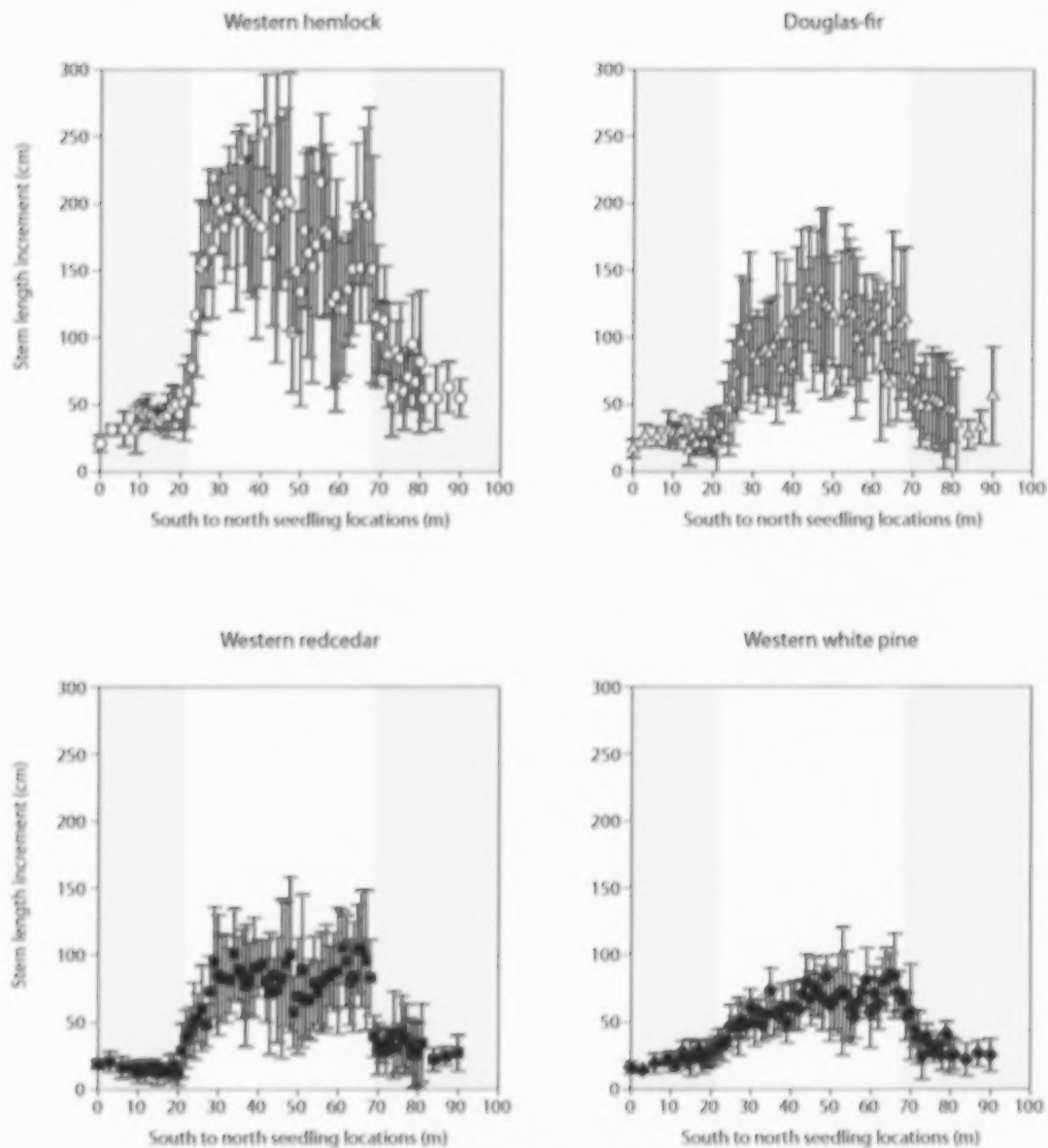


FIGURE 24 Mean stem length increment from 2005 to 2010 at the STEMS 2 light study (HUI10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

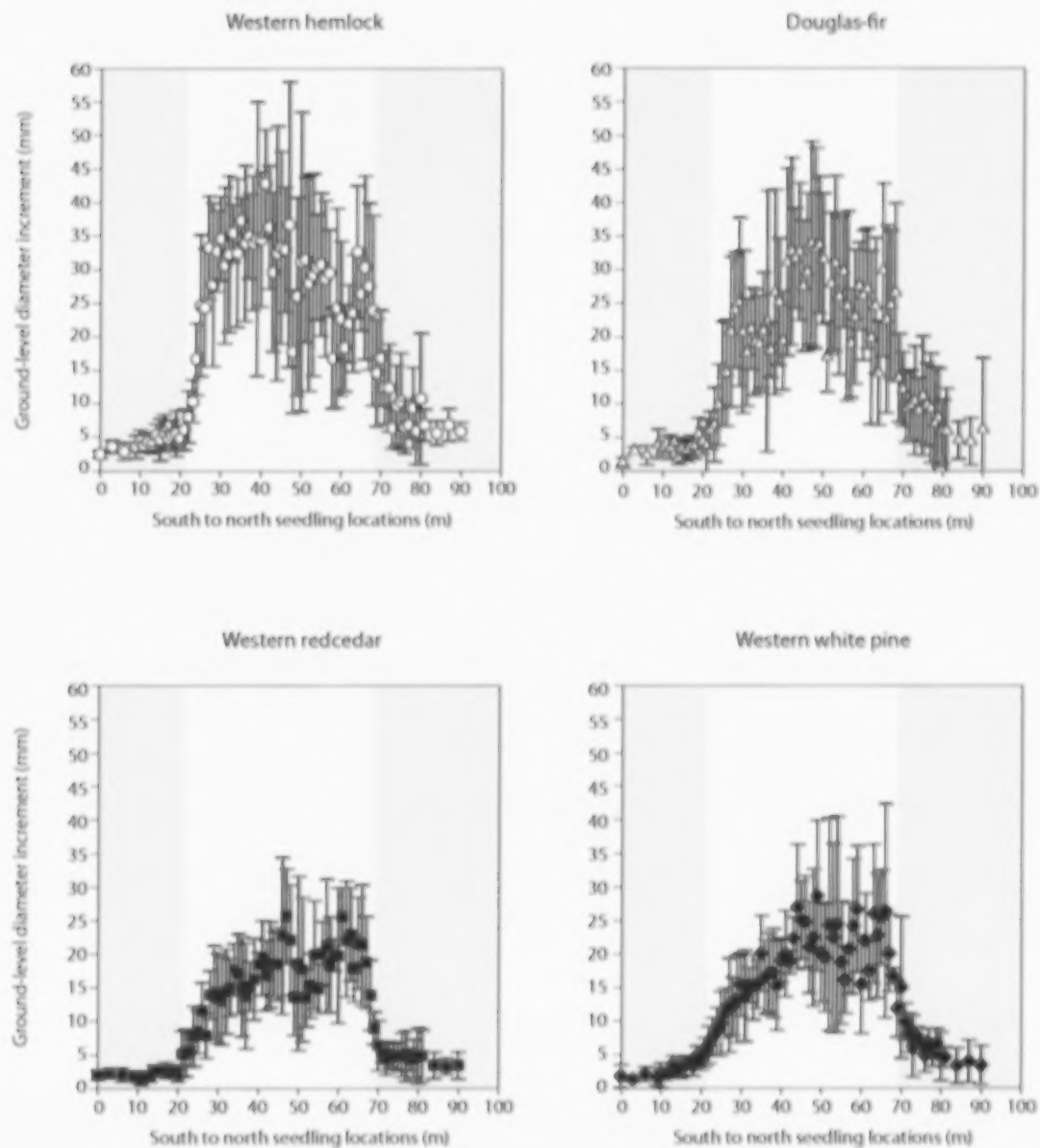


FIGURE 25 Mean ground-level diameter increment from 2005 to 2010 at the STEMS 2 light study (HUI10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

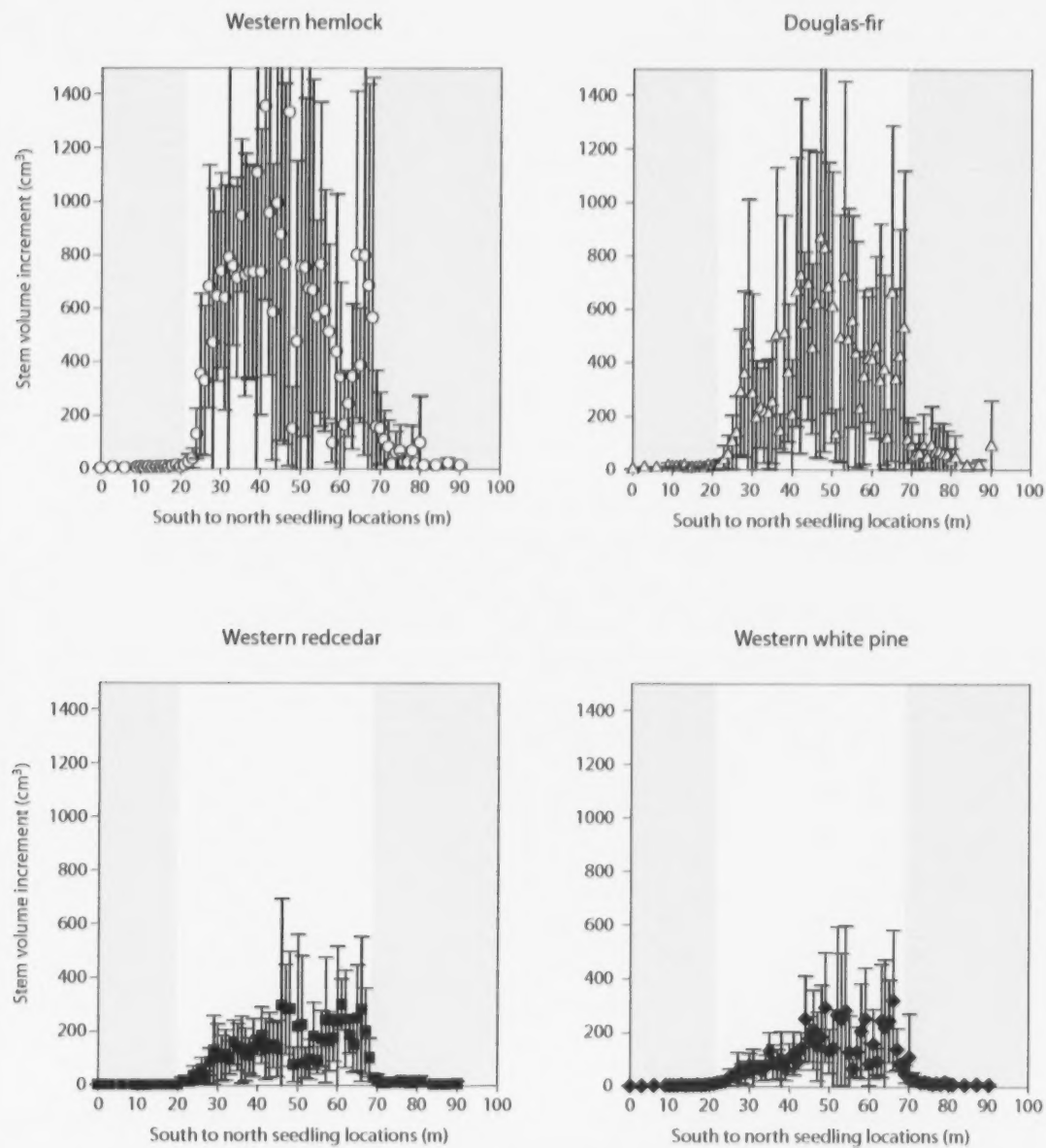


FIGURE 26 Mean stem volume increment from 2005 to 2010 at the STEMS 2 light study (HU10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

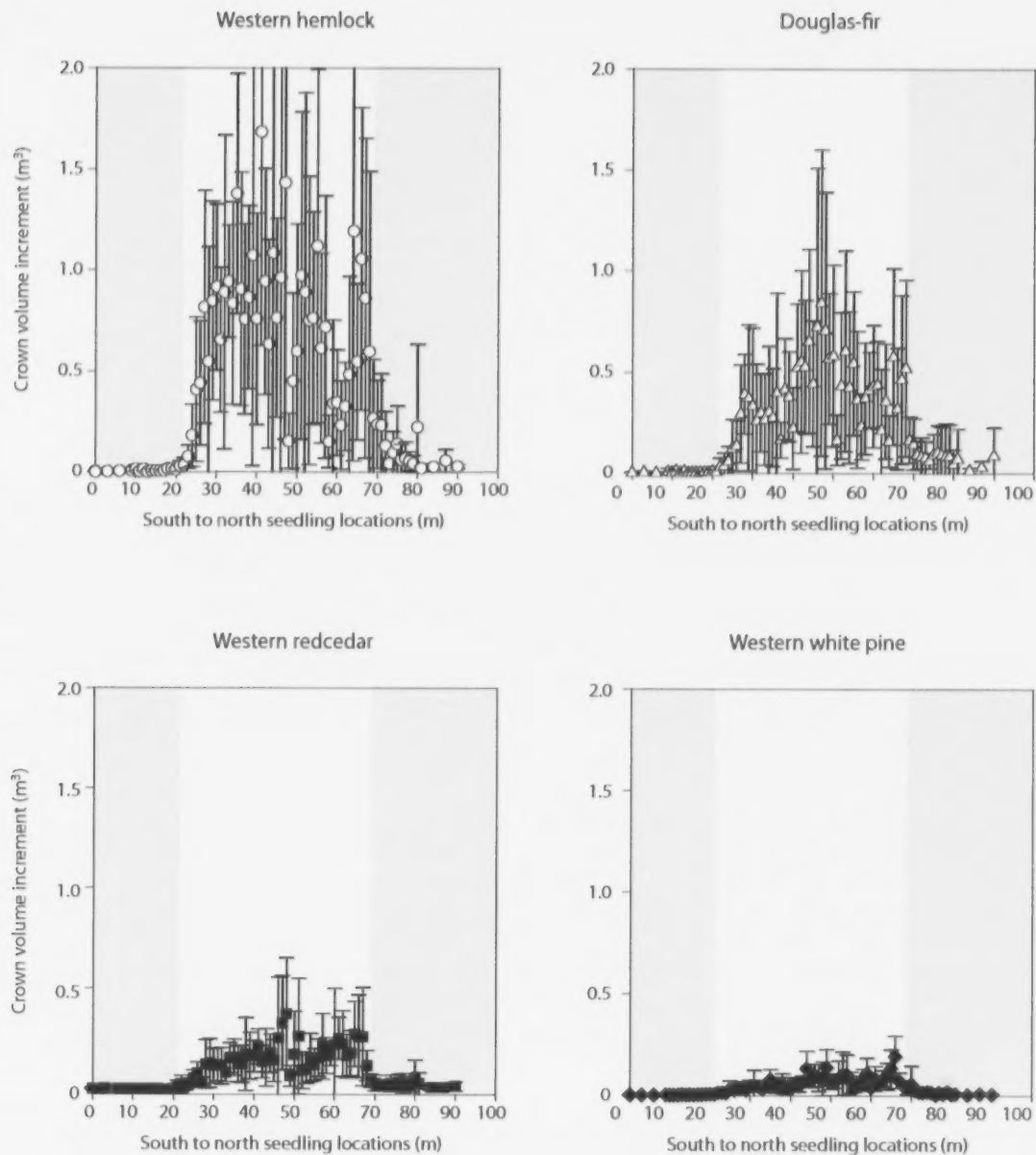


FIGURE 27 Mean crown volume increment from 2005 to 2010 at the STEMS 2 light study (HU10) for four conifer species planted across the gap perpendicular to the forest edge ($N=6$, bars ± 1 SD). Grey shading represents the edge of the gap and residual forest.

was approximately 5 mm under the canopy, was 6–7 mm at the south canopy edge, and then increased to 25 mm at ~15 m from the south edge. Diameter increment tended to decrease across the gap, except for a few tree positions at ~10 m from the north edge. It then declined rapidly to approximately 10 mm within 5 m of the north canopy edge, and remained low (5 mm) under the canopy. Mean stem volume increment reached a maximum (600 cm^3) ~10 m from the south edge but declined rapidly ~5 m from the south edge (Figure 22). Stem volume increment was 11–20 cm^3 under the canopy and approximately 200 cm^3 at the north edge, and then declined to about 15 cm^3 just 5 m into the north canopy. Mean crown volume increment was 0.02–0.05 m^3 under the south canopy to the south edge, and increased to approximately 1 m^3 ~10 m from the south edge (Figure 23). Crown volume increment was variable in the gap and then declined at the north edge from ~1 m^3 to 0.01 m^3 ~10 m across the north edge.

HU10 gap at STEMS 2 In the HU10 light study gap at STEMS 2, mortality of western redcedar seedlings over the whole planting area was 0.6%, the lowest of all four species (Figure 19b). By planting area zone, western redcedar suffered 1% mortality under the north canopy, 0% under the south canopy, and 0.7% in the gap. After 5 years, overall seedling growth means were 15 mm for ground-level diameter, 82 cm for stem length, 94 cm^3 for stem volume, and 0.1 m^3 for crown volume (Table 8). Mean stem length increment was less than 20 cm under the south canopy, increased to 30 cm at the edge, and reached a general maximum of 90 cm ~10 m from the south edge (Figure 24). Stem length increment was constant across the gap but declined abruptly to approximately 40 cm at the north edge and into the north canopy. The pattern of mean ground-level diameter across the gap was similar; it achieved a maximum close to the south edge (Figure 25). Diameter increment was approximately 2 mm under the canopy up to the south canopy edge, and increased to 20 mm at ~20–25 m from the south edge. Mean values remained variable up to ~3 m from the north edge; diameter increment then decreased rapidly to approximately 10 mm, and declined to 5 mm under the north canopy. Mean stem volume increment was 1.7–3.5 cm^3 under the south canopy, and increased to 13 cm^3 at the edge (Figure 26). At 10 m from the south edge, stem volume increment was approximately 100 cm^3 . It increased to about 150 cm^3 at 25 m, then became increasingly variable (between 80 and 300 cm^3), and did not decline consistently until values fell to ~100 cm^3 at the north edge. Into the north canopy, stem volume increment declined to 13 cm^3 in the first 5 m, and then varied between 6 and 17 cm^3 . Crowns decreased in volume after planting under the south canopy, which resulted in negative mean crown volume increment values. Under the south canopy, crown volume increment was 0.002–0.015 m^3 , and then increased to 0.03 m^3 at the south edge; it achieved a maximum of 0.8 m^3 ~10 m from the south edge (Figure 27). Crown volume increment remained highly variable (between 0.15 and 1.7 m^3) across the gap to the north edge, then dropped rapidly to 0.1 m^3 at the north edge. Under the north canopy, crown volume increment was consistently low, and declined to approximately 0.01 m^3 at ~5 m into the canopy but never dropped below 0.005 m^3 .

3.4.3 Douglas-fir

GS10 gap at STEMS 1 In the GS10 light study gap at STEMS 1, mortality of all Douglas-fir seedlings was 12% in the first year after planting, increased to 17% in the second year, and reached 21% after 4 years (Figure 19a). By planting area zone, Douglas-fir suffered 22% mortality under the north canopy, 35.5% under the south canopy, and 15% in the gap. After 5 years, overall seedling growth means were 15 mm for ground-level diameter, 103 cm for stem length, 116 cm³ for stem volume, and 0.16 m³ for crown volume (Table 7). Mean stem length increment was 20 cm under the south canopy, increased to 50 cm at the edge, and reached a general maximum of 120 cm ~15–20 m from the south edge (Figure 20). Stem length increment across the gap was variable but declined to approximately 30 cm at ~5 m from the north edge. Mean ground-level diameter increment was 2.5–3 mm under the canopy and 4 mm at the south canopy edge, and it increased to 20 mm at ~30 m from the south edge (Figure 21). Diameter increment tended to increase across the gap but variability was high. Diameter increment declined rapidly from 20 mm to approximately 5 mm within 5 m of the north canopy edge and remained at this level under the canopy. Mean stem volume increment was 5–10 cm³ up to the south edge, and reached a maximum of 300 cm³ ~20–30 m from the south edge; it then declined rapidly to approximately 100 cm³ ~5 m from the south edge and to 10 cm³ at 5 m into the canopy (Figure 22). Mean crown volume increment was approximately 0.02 m³ in the south canopy, and increased to 0.5 m³ ~20 m from the south edge (Figure 23). It remained the same across the gap, declined to 0.3 m³ ~5 m from the north edge, and was 0.01–0.02 m³ within a few metres of the edge.

HU10 gap at STEMS 2 In the HU10 light study gap at STEMS 2, mortality of all Douglas-fir seedlings was approximately 5% over 4 years, with most mortality occurring in the second year after planting (Figure 19b). By planting area zone, Douglas-fir suffered 7.8% mortality under the north canopy, 6.5% under the south canopy, and 4.3% in the gap. After 5 years, overall seedling growth means were 21 mm for ground-level diameter, 106 cm for stem length, 256 cm³ for stem volume, and 0.26 m³ for crown volume (Table 8). Mean stem length increment was 25 cm under the south canopy to the edge, and increased to a maximum of 130 cm at ~20 m from the south edge (Figure 24). Stem length increment was maintained across the gap to the north edge, where values declined to 70 cm; they further declined to 50 cm under the canopy. Mean ground-level diameter increment was 1–4 mm under the south canopy up to the edge, and increased to 30 mm at ~20 m from the south edge (Figure 25). Diameter increment tended to decrease across the gap to approximately 25 mm, but variability was high. Diameter increment then declined abruptly to 15 mm at the north canopy edge and remained at about 5 mm under the canopy. Mean stem volume increment was 5–14 cm³ under the south canopy and 10 cm³ at the south edge (Figure 26). Stem volume increment then increased to approximately 200 cm³ at 10 m from the south edge, and then further increased to 600–800 cm³ at 25 m from the south edge. Across the rest of the gap, values were variable (between 150 and 800 cm³) and remained at approximately 500 cm³ at the north edge, where values declined to ~80 cm³ within 5 m of the northern canopy. Under the north canopy, stem volume increment was 13–90 cm³. Mean crown volume

increment was 0.001–0.008 m³ under the south canopy and 0.008 m³ at the south edge, then increased to 0.25 m³ at ~10 m from the south edge and reached 0.7 m³ at 25 m beyond the edge (Figure 27). Crown volume increment remained highly variable (between 0.15 and 0.6 m³) across the gap to the north edge, where values were approximately 0.5 m³. Under the north canopy, crown volume increment declined to approximately 0.07 m³ at 5 m but never dropped below 0.01 m³.

3.4.4 Western white pine

GS10 gap at STEMS 1 In the GS10 light study gap at STEMS 1, mortality of all western white pine seedlings was 11% in the first year after planting, and increased to 14% after 4 years (Figure 19a). By planting area zone, western white pine suffered 22% mortality under the north canopy, 39.5% under the south canopy, and 7.5% in the gap. After 5 years, overall seedling growth means were 14 mm for ground-level diameter, 76 cm for stem length, 70 cm³ for stem volume, and 0.06 m³ for crown volume (Table 7). Mean stem length increment was approximately 25 cm under the south canopy, and increased to 100 cm ~30 m from the south edge (Figure 20). Within 10 m of the north edge, stem length increment declined to approximately 30 cm, and was about 25 cm under the north canopy. Mean ground-level diameter increment was 2–4 mm under the south canopy and 4 mm at the south canopy edge, and increased to 22 mm at ~30–40 m from the south edge (Figure 21). Diameter increment tended to increase across the gap to the north edge, but variability was high. Diameter increment declined rapidly from 20 mm to 5 mm within 10 m of the north canopy edge, and remained at approximately 3 mm under the north canopy. Mean stem volume increment was 2–10 cm³ under the south canopy and 10 cm³ at the edge, then increased to 200 cm³ ~30 m from the south edge (Figure 22). Stem volume increment declined rapidly in the last 6 m to 50 cm³ at the north edge, and declined further to less than 10 cm³ within 5 m of the edge. Mean crown volume increment was less than 0.01 m³ under the south canopy, and increased to 0.02 m³ at the edge (Figure 23). It then increased to 0.15 m³ at ~25 m from the south edge. Values remained the same across the gap but decreased to 0.03 m³ ~5 m from the north edge and to less than 0.01 m³ under the north canopy.

HU10 gap at STEMS 2 In the HU10 light study gap at STEMS 2, mortality of all western white pine seedlings was 1.3% (Figure 19b). By planting area zone, western white pine suffered 0% mortality under the south canopy, 2.1% under the north canopy, and 1.4% in the gap. After 5 years, overall seedling growth means were 17 mm for ground-level diameter, 58 cm for stem length, 85 cm³ for stem volume, and 0.04 m³ for crown volume (Table 8). Mean stem length increment was approximately 20 cm under the south canopy and 30 cm at the south edge, and increased to 80 cm ~30 m from the south edge (Figure 24). Within 5 m of the north edge, stem length increment declined to approximately 50 cm and was about 25 cm under the north canopy. Mean ground-level diameter increment was 2 mm under the south canopy and 5 mm at the south canopy edge, and increased to 25 mm about 25 m from the south edge (Figure 25). Ground-level diameter increment tended to increase across the gap to the north edge, but variability was high. Diameter increment then declined rapidly from 20 mm to approximately 15 mm within 3 m

of the north canopy edge and remained at this level under the north canopy. Mean stem volume increment was 1–7 cm³ under the south canopy and 9 cm³ at the south edge (Figure 26). At 10 m from the south edge, stem volume increment was approximately 60 cm³, and increased to approximately 200 cm³ at 25 m. Values were then variable (between 70 and 300 cm³), then declined to 80 cm³ at the north edge, and further declined to approximately 20 cm³ within the first 5 m under the north canopy. Mean crown volume increment was 0.004–0.005 m³ under the south canopy and 0.005 m³ at the south edge, and then increased to 0.05 m³ at ~10 m from the south edge and to 0.1 m³ at 25 m beyond the edge (Figure 27). Crown volume increment remained highly variable (between 0.06 and 0.14 m³) across the gap to the north edge, where values were approximately 0.05 m³. Under the north canopy, crown volume increment declined to approximately 0.015 m³ within 5 m of the edge but never dropped below 0.004 m³.

3.5 Modelling of Growth in Response to Gap Conditions

The forest gap environment consists of a complex interweaving of atmospheric and edaphic factors. These factors are characterized by gradients that depend on cardinal direction and edge location (Spittlehouse et al. 2004; Walters et al. 2006; Voicu and Comeau 2006). Results discussed in the following sections provide a general overview of trends in the collected data for the first 5 years after planting at each gap. For this analysis we used the log of stem volume increment as the dependent variable. Depending on the gap location, gap T values on any day may have achieved 1.0 for variable periods. For modelling purposes, we estimated T for each growing season, and averaged this for the 5-year period of growth increment. We expressed soil moisture as a proportion of the measurement period where soil conditions were sufficient to cause plant stress (Section 2.4.2), referred to as the soil moisture deficit period. These values were then averaged for multiple years. We calculated VPD as the sum of number of hours in each annual measurement period that the deficit was beyond the stress threshold of 2 kPa, referred to as the evaporative demand period, and averaged multiple years' readings.

Although other non-linear models have traditionally been used to describe plant growth response (i.e., Michaelis-Menton, Gompertz), we felt that they had poor descriptive power. Instead, we believed that the General Additive Model (GAM) procedure in SAS, with its inclusion of co-variables for soil and air moisture, would better explain some of the variation in growth response. We investigated the appropriateness of the model by using partial residual plots (Appendix 7), and it appeared to fit the residuals well. Table 9 presents the model estimate parameters for both light study gaps. Figure 28 (GS10) and Figure 30 (HU10) summarize the actual log stem volume increment values and predicted T values for the four conifer species planted in the light study gaps at STEMS 1 and STEMS 2. The complex curves for the predicted values describe a three-dimensional response surface. Figure 29 (GS10) and Figure 31 (HU10) focus more closely on the predicted effect of T, soil drying, and evaporative demand on seedling stem volume of the four conifer species for selected combinations of soil and atmospheric conditions. Each graph in these figures shows a different combination of SMDP and EDP conditions, with SMDP changing in the vertical (0, 0.15, and 0.3 of period >1 MPa) and EDP increasing horizontally (20, 50, and 80 hours >2 kPa).

TABLE 9 General additive model parameter estimates and significance tests for the relationship between log stem volume increment (5 years) and average corrected annual transmittance of above-canopy light (T), soil moisture deficit period (SMDP), and evaporative demand period (EDP) at the GS10 and HU10 light study gaps. Cw: western redcedar; Fd: Douglas-fir; Hw: western hemlock; Pw: western white pine.

Species	Parameter	Estimate	Standard error	t value	Probability	N	RMSE	R ²
GS10 light study gap at STEMS 1								
Cw	Intercept	3.699	0.270	13.68	0.0000	357	1.080	0.96
	SMDP	-5.605	0.705	-7.95	0.0000			
	EDP	-0.019	0.003	-6.22	0.0000			
	Linear (T)	5.102	0.569	8.96	0.0000			
	Spline (T)				0.0001			
Fd	Intercept	4.095	0.222	18.42	0.0000	302	0.798	0.95
	SMDP	-7.545	0.580	-13.02	0.0000			
	EDP	-0.001	0.003	-0.22	0.8293			
	Linear (T)	2.023	0.470	4.30	0.0000			
	Spline (T)				0.0001			
Hlw	Intercept	4.484	0.299	15.01	0.0000	221	0.755	0.96
	SMDP	-8.422	0.950	-8.87	0.0000			
	EDP	0.000	0.003	0.02	0.9819			
	Linear (T)	2.249	0.619	3.63	0.0004			
	Spline (T)				0.0001			
Pw	Intercept	2.216	0.188	11.81	0.0000	346	0.772	0.99
	SMDP	-3.607	0.502	-7.19	0.0000			
	EDP	-0.008	0.002	-3.89	0.0001			
	Linear (T)	4.485	0.369	12.16	0.0000			
	Spline (T)				0.0001			
HU10 light study gap at STEMS 2								
Cw	Intercept	2.435	0.188	12.939	0.0000	472	1.123	0.97
	SMDP	-18.257	1.912	-9.549	0.0000			
	EDP	-0.023	0.005	-4.571	0.0000			
	Linear (T)	5.462	0.524	10.418	0.0000			
	Spline (T)				<0.0001			
Fd	Intercept	3.098	0.189	16.419	0.0000	453	1.093	0.98
	SMDP	-15.810	1.948	-8.116	0.0000			
	EDP	-0.036	0.006	-6.548	0.0000			
	Linear (T)	6.925	0.566	12.226	0.0000			
	Spline (T)				0.0055			
Hlw	Intercept	3.963	0.207	19.099	0.0000	467	1.20	0.93
	SMDP	-22.301	2.139	-10.426	0.0000			
	EDP	-0.041	0.006	-7.225	0.0000			
	Linear (T)	5.954	0.586	10.158	0.0000			
	Spline (T)				<0.0001			
Pw	Intercept	1.779	0.179	9.964	0.0000	472	0.973	0.98
	SMDP	-11.878	1.792	-6.628	0.0000			
	EDP	-0.021	0.005	-4.503	0.0000			
	Linear (T)	7.008	0.532	13.173	0.0000			
	Spline (T)				0.0008			

In the brightest part of the gaps, maximum T integrated over the growing season was ~0.8 for the GS10 light study and ~0.7 for the HU10 study. In just the open gap, rough average values of SMDP were 0.1 at GS10 and 0.01 at HU10; for EDP, these values were 115 hours at GS10 and 56 hours at HU10. In the GS10 forest, average SMDP was 0.3 and EDP was 35–100 hours; in the HU10 forest, average SMDP was 0.07 and EDP was 29–70 hours.

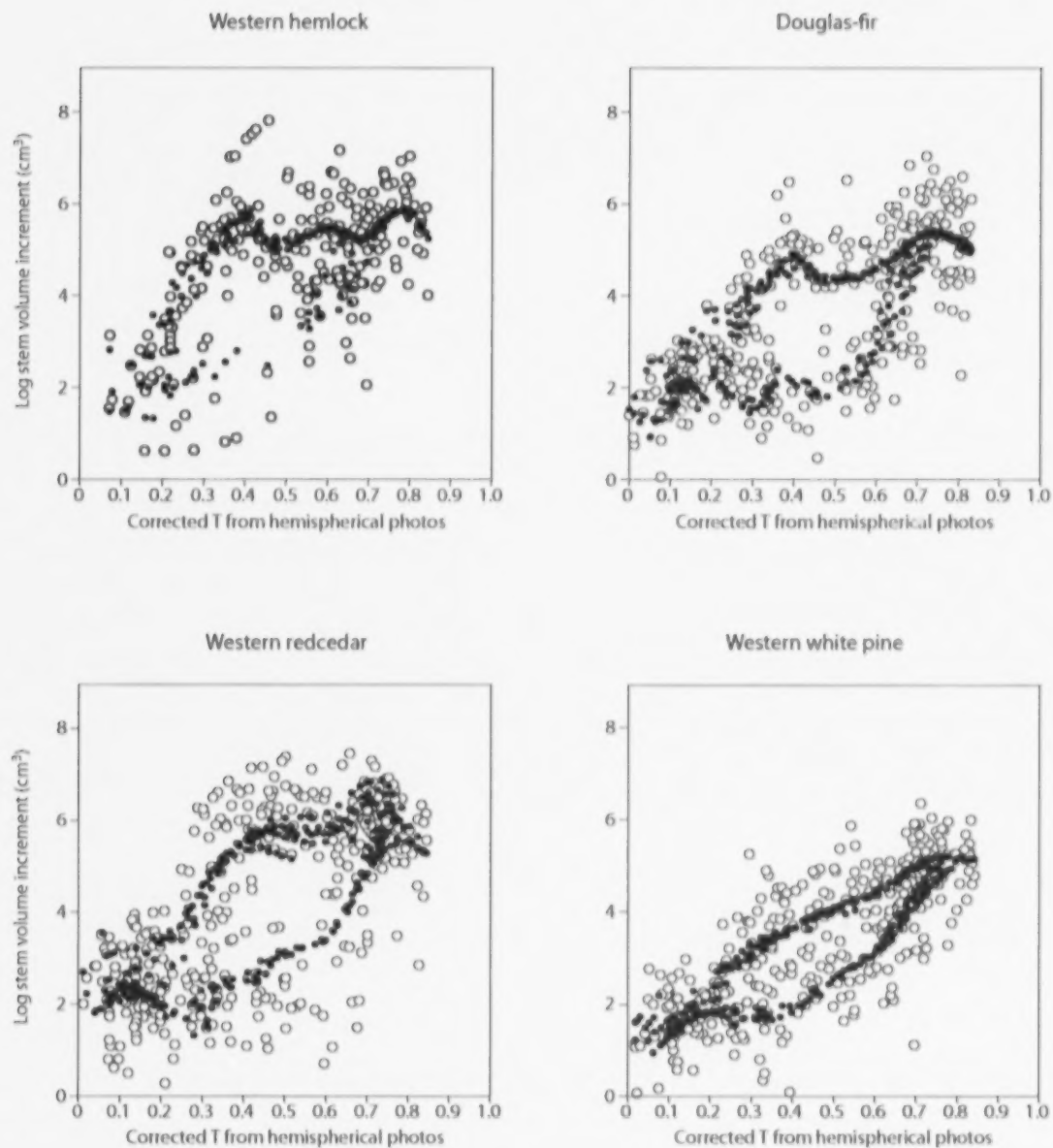


FIGURE 28 Relationship between log stem volume increment from 2003 to 2008 and average corrected transmittance of above-canopy light (T) from hemispherical photos for four conifer species planted at the STEMS 1 light study (GS10) ($n = 221$, 352, 302, and 346 for western hemlock, western redcedar, Douglas-fir, and western white pine, respectively). The circles are individual tree measurements and the black dots are predicted values from the equations in Table 9. Partial residual plots are shown in Appendix 7.

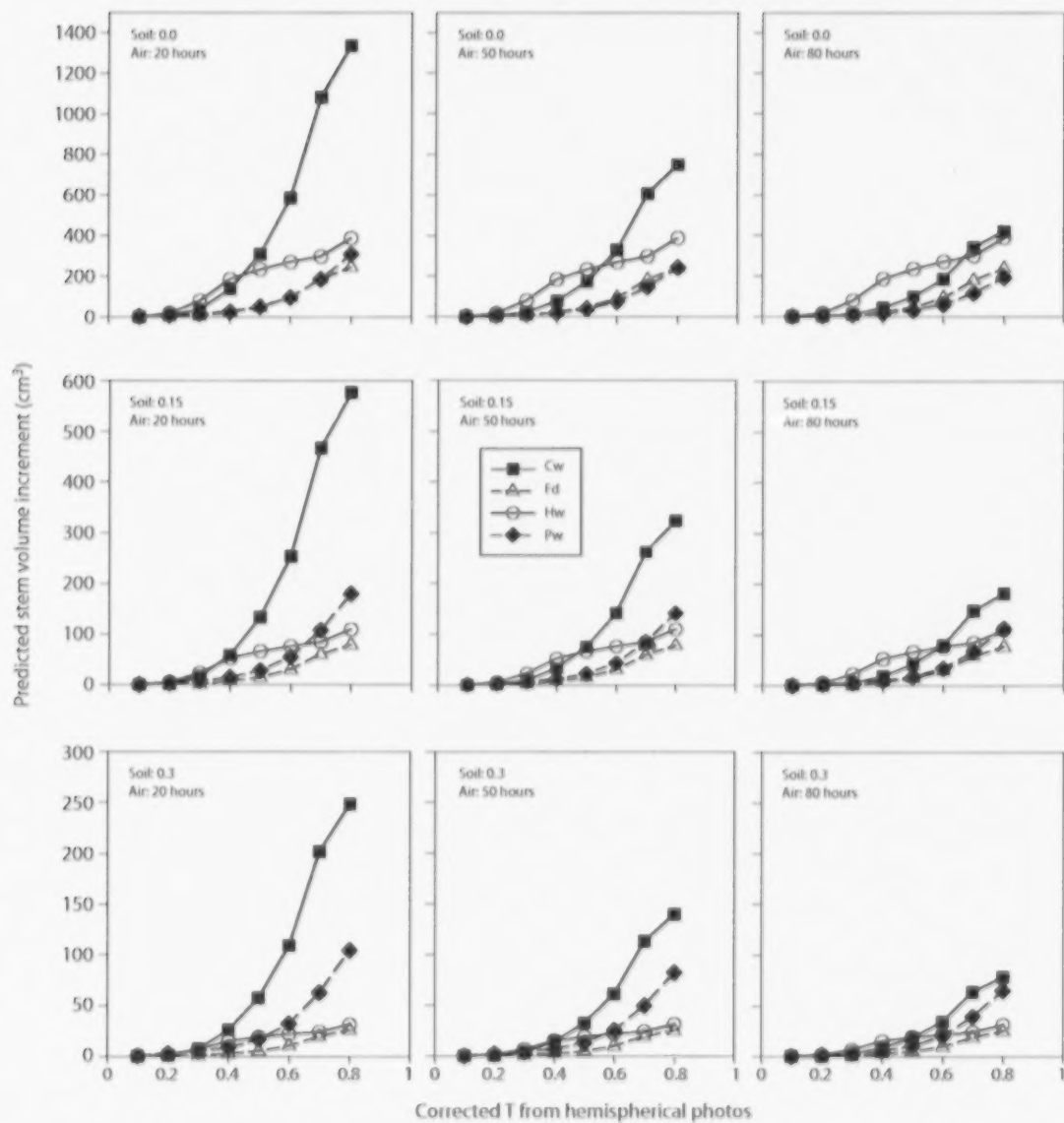


FIGURE 29 Predicted relationships between stem volume increment from 2003 to 2008 and average corrected transmittance of above-canopy light (T) from hemispherical photos at three levels of air and soil moisture stress for four conifer species at the STEMS 1 light study (GS10). See partial residual plots in Appendix 7.

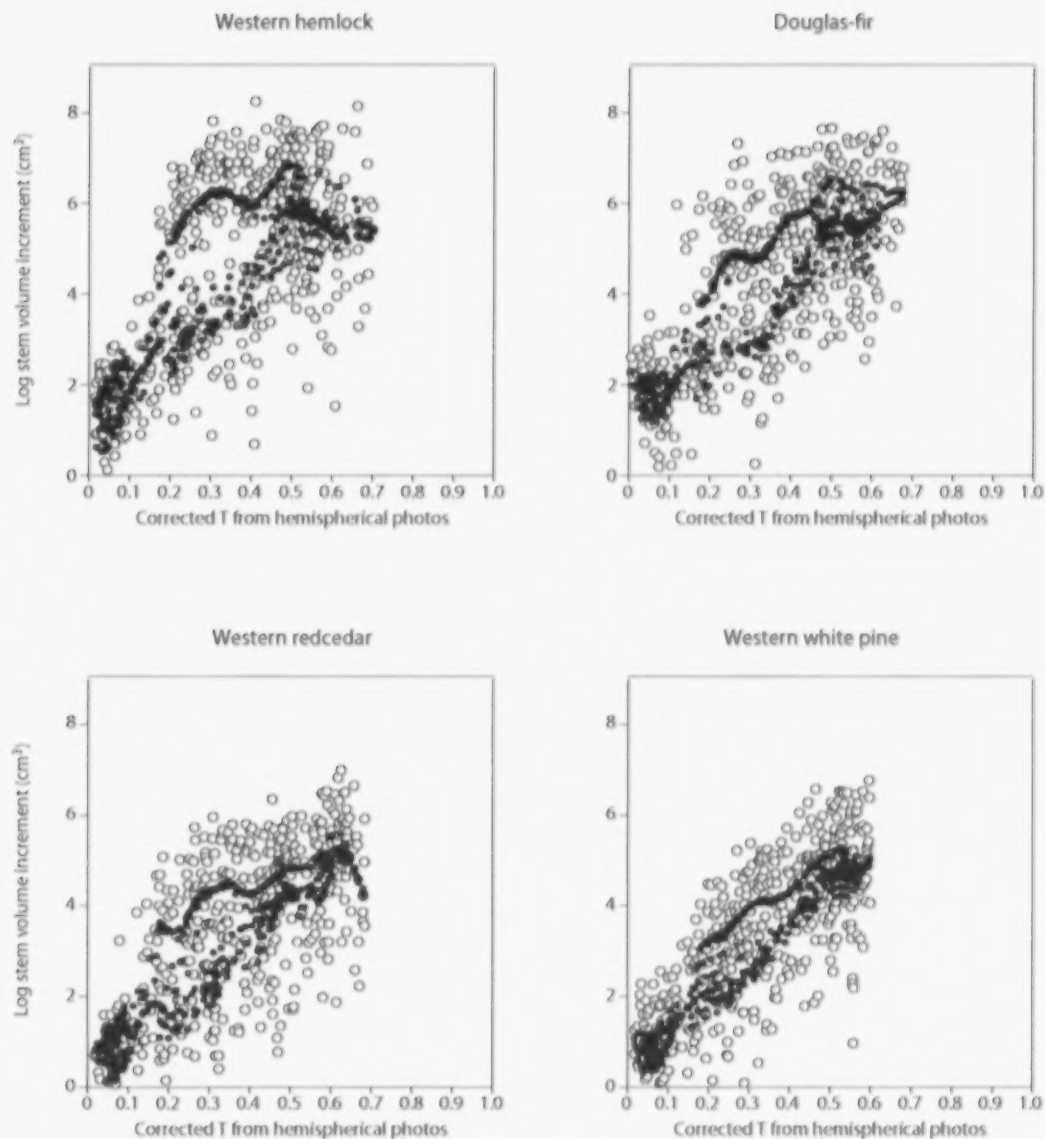


FIGURE 30 Relationship between log stem volume increment from 2005 to 2010 and average corrected transmittance of above-canopy light (T) from hemispherical photos for four conifer species planted at the STEMS 2 light study (HU10) ($n = 467$, 472, 453, and 472 for western hemlock, western redcedar, Douglas-fir, and western white pine, respectively). The circles are individual tree measurements and the black dots are predicted values from the equations in Table 9. Partial residual plots are shown in Appendix 7.

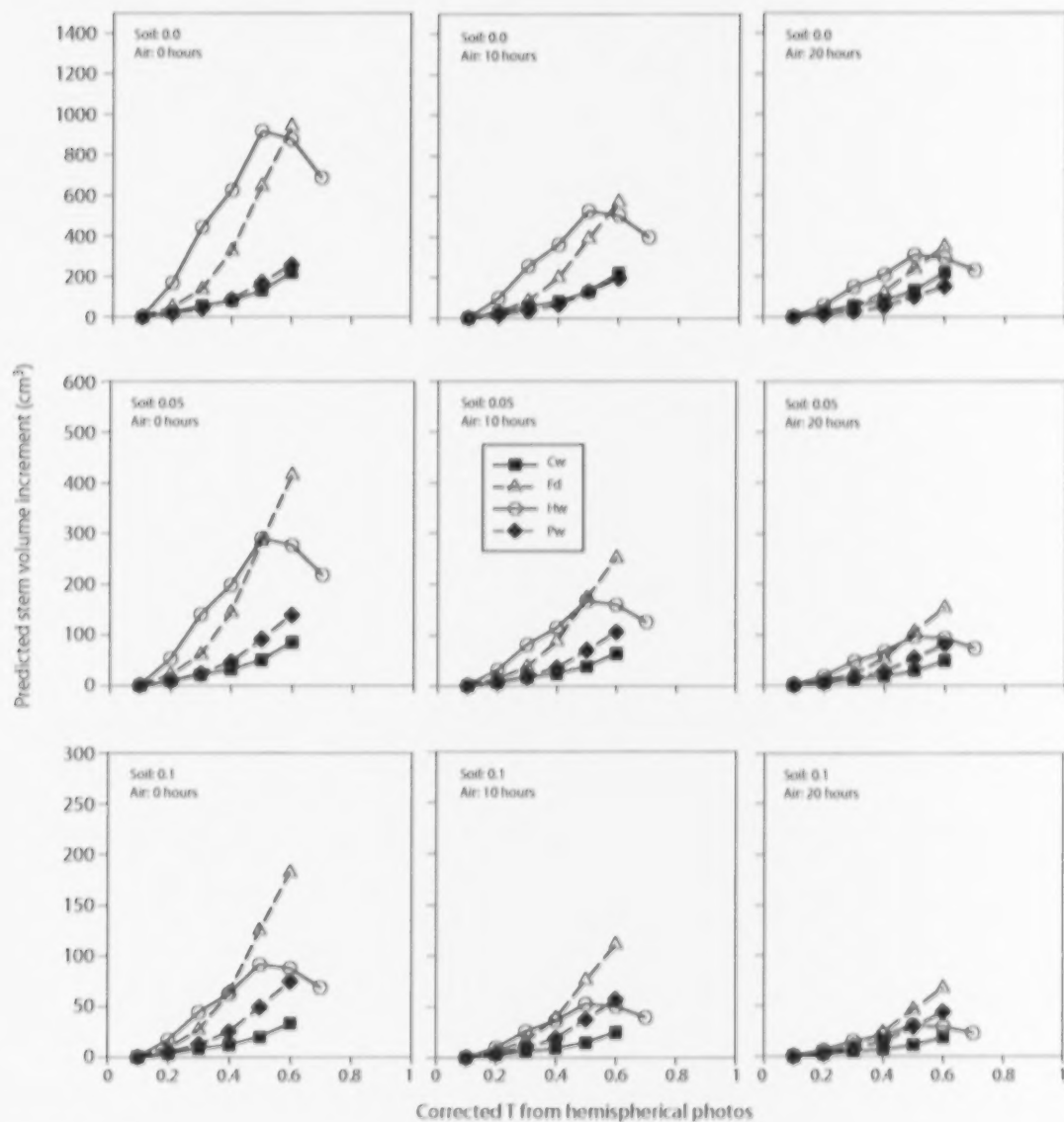


FIGURE 31 Predicted relationships between stem volume increment from 2005 to 2010 and average corrected transmittance of above-canopy light (T) from hemispherical photos at three levels of air and soil moisture stress for four conifer species at the STEMS 2 light study (HU10). See partial residual plots in Appendix 7.

3.5.1 Western hemlock

GS10 gap at STEMS 1 Figure 28 shows that stem volume increment values were distributed between -0.5 and 8 cm^3 for western hemlock at the GS10 light study gap. Stem volume increment increased relatively rapidly from 1 cm^3 to -5 cm^3 between 0.1 and 0.3 T. Between 0.3 and 0.8 T, there was practically no further gain in stem volume as the predicted curve became flatter but not completely asymptotic. A few points trace the lower curve of stem volume increment response at equivalent T levels owing to other factors (i.e., moisture stress) in locations where moisture is limiting but not necessarily light. Most western hemlock mortality occurred in locations of high water stress. In Figure 29, the T curves of predicted stem volume increment show a rapid increase in stem volume up to about 0.4 T, followed by a more gradual slope (see Figure A7.1). The curves were not sensitive to increased EDP up to 80 hours. Table 9 shows that this term was not significant in the model, but T and SMDP were significant. Stem volume increment decreased with increasing SMDP, and growth ranking decreased with increasing water stress compared to western white pine.

HU10 gap at STEMS 2 Figure 30 shows that stem volume increment values were distributed between -0 and 8 cm^3 for western hemlock at the HU10 light study gap. Values increased relatively rapidly from less than 1 to -6 cm^3 between 0.02 and 0.3 T. Between 0.3 and 0.8 T, there was practically no further gain stem volume as the predicted curve became flatter. The lower predicted curve indicated that western hemlock growth was affected by moisture stress over the whole range of T. In Figure 31, the growth curves show a rapid increase in stem volume up to about 0.5 T, followed by a decrease in growth. The partial residual plot also shows that stem volume reaches a maximum between 0.3 and 0.5 T (Figure A7.4). This indicates that, for western hemlock, light saturates even at the low light levels encountered in the HU10 gap. The curves were sensitive to increasing SMDP and EDP. Table 9 shows that all terms in the model were significant. Stem volume increment for western hemlock was the highest of all species in the gap; Douglas-fir ranked second. At higher SMDP and EDP, western hemlock stem volume increment diminished compared to that of Douglas-fir, and the ranking changed at T levels greater than 0.5 . At T levels less than 0.5 , western hemlock retained its greater stem volume increment, but even this was reduced at greater SMDP.

3.5.2 Western redcedar

GS10 gap at STEMS 1 Figure 28 shows that stem volume increment values were distributed between -0 and 7.5 cm^3 for western redcedar at the GS10 light study gap. The upper predicted curve has a parabolic form with an inflection point at approximately 0.4 T at a log value of -5 cm^3 . Values increased to 6 cm^3 at T values above -0.8 (see Figure A7.1). The lower predicted curve indicates that western redcedar growth was affected by moisture stress over the whole range of T. Table 9 shows that all terms in the model were significant for this species. In Figure 29, predicted stem increment of western redcedar shows an interesting response to light above 0.5 T. The data suggest a stronger growth response to light (in the absence of moisture stress) than other conifer species at this site; however, western redcedar growth appeared

to be reduced by both increasing SMDP and increasing EDP. Western redcedar always maintained its ranking but was much reduced at average gap moisture conditions.

HU10 gap at STEMS 2 Figure 30 shows that stem volume increment values were distributed between -0 and 7 cm^3 for western redcedar at the HU10 light study gap. The upper predicted curve has a parabolic form with an inflection point at approximately 0.4 T at a log value of -4.0 cm^3 . In Figure 31, the predicted curves show that stem volume increased with increasing T and no sign of light saturation (see Figure A7.4). The slope of the T to stem volume curves declined with increasing SMDP and EDP. Table 9 shows that all terms in the model were significant. Western redcedar had the poorest growth of all four species on this site (see discussion below).

3.5.3 Douglas-fir

GS10 gap at STEMS 1 Figure 28 shows that stem volume increment values were distributed between -1 and 7 cm^3 for Douglas-fir at the GS10 light study gap. The upper predicted curve has an inflection point at 0.3 T at a log value of -5 cm^3 , but the curve does not become asymptotic and continues to increase to -5.5 at maximum T . In Figure 29, the predicted growth curves also show that Douglas-fir responded to increasing light, with no suggestion of light saturation (see Figure A7.1). Lower points on the predicted curve indicate that Douglas-fir growth was affected by moisture stress over the whole range of T . Table 9 shows that the effect of EDP in the model was not significant (see Figure A7.3), which indicates that soil moisture was mainly responsible for the growth effects (excepting unmeasured effects). The predicted curves (Figure 29) also indicate that Douglas-fir grew very similarly to western white pine when SMDP was low, but that Douglas-fir ranked lower than western white pine and all other species as soil moisture stress increased.

HU10 gap at STEMS 2 Figure 30 shows that stem volume increment values were distributed between -0 and 7.6 cm^3 for Douglas-fir at the HU10 light study gap. The upper predicted curve increases without inflection point to -6 cm^3 at maximum T . In Figure 31, the predicted growth curves also show that Douglas-fir responded to increasing light, with no suggestion of light saturation (see Figure A7.1). Higher T values may have been expected to result in greater log values. The lower predicted curve indicates that Douglas-fir growth was affected by moisture stress over the whole range of T . Table 9 shows that all terms in the model were significant. At the HU10 site, Douglas-fir showed a strong growth response (similar to western hemlock) when SMDP and EDP are moderate to low, but it was also able to respond to higher light levels.

3.5.4 Western white pine

GS10 gap at STEMS 1 Figure 28 shows that stem volume increment values were distributed between -0.1 and 6.5 cm^3 for western white pine at the GS10 light study gap. The upper predicted curve has a slightly parabolic form, with little or no inflection point. Log values increased to approximately 5 cm^3 at maximum T . Light levels in the gap were insufficient for maximum growth of

this species (see Figure A7.1). The lower predicted curve indicates that western white pine growth was affected by moisture stress over the whole range of T . Table 9 shows that T , $SMDP$, and EDP were all significant (see Figures A7.2 and A7.3). In Figure 29, predicted curves show that western white pine grew very similarly to Douglas-fir at low soil moisture stress. Western white pine tolerated soil moisture deficits comparatively well but was somewhat susceptible to increasing evaporative demand.

HV10 gap at STEMS 2 Figure 30 shows that stem volume increment values were distributed between -0 and 6.8 cm^3 for western white pine at the HV10 light study gap. The upper predicted curve increases with little deviation to -5 cm^3 at maximum T (see Figure A7.4). Light levels in the gap are insufficient for maximum growth of this species and higher T values may be expected to result in greater stem volume. The lower predicted curve indicates that western white pine growth was affected by moisture stress over the whole range of T . Table 9 shows that all terms in the model were significant. Western white pine and western redcedar show very similar predicted growth response to T at low $SMDP$; however, western white pine had higher stem volume increment at greater $SMDP$, which was maintained over increasing EDP .

4 DISCUSSION

Because the lack of replication limits the value of formal statistical comparisons, we discuss the regeneration response to the measured local conditions at the GS10 and HV10 light study gaps separately. More sophisticated model development may be applied in later reports or articles; the addition of STEMS 3 (PP10) data may provide greater statistical power to future comparisons of species growth and survival at each site.

4.1 GS10 Gap at STEMS 1

Plant moisture stress can reduce growth response by limiting photosynthate production when light levels are ideal for rapid growth (Cleary and Ferrell 1970). At the GS10 light study gap, a zone approximately 3–5 m from the north edge always dried out during the growing season regardless of the year; however, during dry years, this zone could extend out to 20 m. The length of time this dry zone persisted, or the soil moisture deficit period, determined the gap's "dryness." A similar zone was present on the south side of the gap; it extended from the edge of the planting area to just beyond the edge of the south residual stand (Chen et al. 1993; Gray et al. 2002; Spittlehouse et al. 2004; Voicu and Comeau 2006; Walters et al. 2006). The dryness of this gap was influenced by its moderate annual rainfall (1195–1886 mm) and relatively thin soils (Section 2.1), and bedrock was close to the surface in places. Soils usually began to dry out in June and would pass through several wetting and drying cycles into October. Under the residual canopy, soils dried out first and rehydrated last, and the gaps remained moist longer.

Maximum T at this gap was -0.8 at ~ 30 – 40 m from the south edge and decreased to about 0.2 – 0.3 at the south edge. The light regime at the edges of the north and south residual canopies differed considerably; light transmittance levels were higher (0.5 – 0.7) on the north side close to the edge because of direct light penetration (Dignan and Bren 2003; Spittlehouse et al. 2004).

Seedling growth did not appear to respond to these higher light levels compared with growth response in areas elsewhere in the gap that had similar light levels (Canham et al. 1990; Coates 2000). Vapour pressure deficit measurements confirmed that evaporative demand due to radiant heating from direct sunlight was elevated. The resulting evaporative stress on planted seedlings was most intense just a few metres from the north edge, remained elevated up to 30 m south of the north edge, and decreased further south under the influence of the shading zone associated with the southern residual stand. Evaporative demand during the growing season was lowest for the planting area under the south residual canopy and approximately 6 m from the south edge, beyond which it increased steeply over ~20 m, with a midpoint at ~15 m from the south edge.

Western hemlock responded most vigorously; it ranked the highest for stem volume increment of all four species, as might be expected for a shade-tolerant species in a light-limiting environment (Mailly and Kimmins 1997). Growth of the western redcedar and western hemlock seedlings generally reached a maximum in the zone of rapidly changing evaporative demand 10–20 m from the south edge. At that location, light levels were sufficient (0.3–0.7 T) and soil moisture and evaporative demand were low enough to promote a vigorous growth response. Western redcedar and western hemlock both tolerate shade and may maximize growth at lower light levels than Douglas-fir and western white pine in this zone (Klinka et al. 1992; Drever and Lertzman 2001). Western redcedar responded particularly well in this zone, but its response appeared to decline across the gap as moisture demands increased, as demonstrated by the partial residual plots (Figure A7.2). Western hemlock did not respond as vigorously as western redcedar in this zone, but it was less affected by gap conditions. The predicted growth (Figure 29) reflected this observation for western redcedar, which showed a very steep response to T at low soil moisture deficit period and evaporative demand potential and significant effects on growth with increasing moisture stress. Western hemlock showed an elevated response at low light, which was maintained at higher light levels, and no additive effect of evaporative demand.

Under the residual stand, seedling growth, for all species, was generally at a minimum, and mortality was highest. This was related to the combined effect of low light, from a reduction in transmitted light by the residual canopy, and longer periods of higher soil moisture potentials from underground root competition (Lindh et al. 2003). Seedling mortality tended to be greater under the canopy (38% north canopy, 32% south canopy) than in the gaps (10%). Mortality was higher on the south side for all species except western hemlock, which had slightly higher values on the north side. Mortality most likely resulted from the combined effect of low light and moisture stress, but the generally greater effect on the south side shows low light is an important factor. If moisture stress were paramount, then mortality on the north side, with its soil moisture stress and higher evaporative demand, should be greater; however, the results suggest that higher light levels afford some protection by raising the seedling above the light compensation point for longer periods. However, lack of light is unlikely to be the major cause of mortality for the western hemlock seedlings. This species was likely the most shade-tolerant of the species (Carter and Klinka 1992) used in this study. Excepting other factors, such as disease, insects, or poor stock quality, we speculate that western

hemlock must be very sensitive to underground competition on dry sites (Christy 1986). All the seedlings were planted by one worker, a known seedlot was used with a PSB 1+0 412A stock type (Appendix 1), no infestations of any kind were noted, and the whole area was protected from browsing with a perimeter fence; however, the site was subject to significant vegetation competition from salal and from bracken fern in summer.

Seedling growth and light were related in a curvilinear relationship (Wright et al. 1998), depending on relative shade-tolerance ranking (Carter and Klinka 1992; Coates and Burton 1999). Stem volume increment for western hemlock and western redcedar slows within the range of T measured (i.e., 0.3 and 0.8, respectively), although other workers found that growth increased steadily with increasing radiance all the way to full sunlight for western hemlock and western redcedar (Wang et al. 1994; Wright et al. 1998; Coates and Burton 1999). Douglas-fir and western white pine do not show a pronounced inflection in the light response curve at the maximum T measured in this gap. The slope of increasing growth with increasing T at higher T values appears to be steeper for western white pine. The growth of Douglas-fir was ranked third, with a stem volume increment of 115 cm^3 for the whole stand (including all light environments), and for mortality was ranked second. The existing residual stand is mainly Douglas-fir (although planted), and the site index is between 31 and 34 (probably on the lower side for this particular site). Our data show that Douglas-fir does not seem to grow as well as western redcedar, which had low mortality and the best response at low moisture stress and moderate light. Modelling indicated that Douglas-fir was insensitive to EDP, but growth was reduced by increasing soil moisture deficit period, and the growth response increased at higher light levels, with no levelling off at the highest T values. These observations suggest that Douglas-fir is unable to reach its full potential in this gap because of its relative shade-tolerance ranking. It requires full sunlight to achieve maximum growth rates (Drever and Lertzman 2001). Another factor that may explain the performance of Douglas-fir was the presence of needle cast from the leaders and some upper branches in the last 2 years. The same argument concerning light response also applies to western white pine. Western white pine had the lowest overall ranking for stem volume increment and had similar mortality to Douglas-fir. Lack of light may explain the growth ranking and response to light of these two species at this site.

Western redcedar appears to grow comparatively well in the GS10 light study gap, which has a submesic-mesic soil moisture regime. Western hemlock ranked highest (by a small amount) for average stem volume increment, but western redcedar was very similar. Its mortality was low and its health was good. Several factors may influence the success of western redcedar on this site. For instance, every gap size has a unique light profile. Due to its particular shade tolerance, western redcedar may be ideally suited to gaps of this size. Also, Carter and Klinka (1992) found a tendency for this conifer to be more shade tolerant on slightly drier sites. Western redcedar may possibly gain some advantage on this site due to the indeterminate nature of its vegetative shoot development (Krasowski and Owens 1991). Western redcedar may slow or cease growth if conditions are poor and resume growth when conditions improve (Buckland 1956; Walters and Soos 1963), although its tolerance to water deficit is rated as medium (Klinka and Brisco 2009).

Western hemlock height growth may not be strictly deterministic (Walter and Soos 1963; Mitchell and Arnott 1995), and Douglas-fir and perhaps western white pine may retain some ability to re-flush during the growing season (Williams 1968). However, severe moisture stress can cause these species to form buds and enter dormancy early, thus shortening the growing period. A poor growth year can also affect growth in the following year due to reduced or incomplete resting shoot development (Khan et al. 1996). Reduced photosynthate accumulation will also affect diameter growth and root and canopy development (Simpson 1981). The length and timing of the period of stress could also be an important factor in the performance of the four conifer species in this study.

4.2 HU10 Gap at STEMS 2

Light levels in the gap varied by a few percent from year to year, but transmitted light through the south residual canopy was fairly constant up to the edge of the residual stand (0.2 T or less, with lowest values of <0.05). As for GS10, north-side light levels and temperatures were higher in the residual stand close the edge because of direct light penetration. Generally, seedling growth was maintained up to the north edge but declined beyond the edge into the northern residual stand. Underground root competition from the residual stand may have affected seedling growth. Soil moisture deficit period was 0 up to the north edge and 3 m into the north residual canopy but increased further into the canopy. The HU10 site has a 20% slope down to the north edge, and water seepage occurred in all but the driest times of the year. Moisture persisted at the site partly because of the hill to the south and the high annual rainfall, which ranged from a comparative low of 1850 mm in 2009 to 3032 mm in 2007. During wet spells, the soils close to the northern edge of the HU10 gap became saturated and ephemeral streams often formed.

Since photosynthate production does not appear to be limited by soil moisture stress at the north edge of this gap, the reduction in seedling growth was likely related to the high evaporative demand in this zone, which remained high up to about 20 m into the gap from the north edge but decreased under the shade of the residual stand to the south. The zone of shading from the southern edge was substantial because the residual trees were more than 30 m high and the slope exaggerated the length of the shadows. Evaporative demand during the growing season was lowest in the planting area under the south residual canopy and approximately 25 m out from the south edge.

The absence of soil moisture stress in the gap and an extended zone of low evaporative demand might indicate a substantial growth response for seedlings that are able to use the light levels available; growth was maintained up to the north edge of the gap. Maximum T at this site was ~0.7 at ~30–40 m from the south edge, and decreased to 0.1–0.2 at the south edge. Western hemlock responded vigorously, and ranked the highest for stem volume increment of all four species, as might be expected for a shade-tolerant species in a light-limiting environment. The model showed that stem volume increment increased with increasing T up to a clear maximum value. The drop-off in response at higher T is presumably because the seedlings were both light saturated and under the influence of increasing evaporative demand in less favourable growing spots. The model indicated that both soil moisture deficit period and evaporative demand potential were significant. Douglas-fir responded with unexpected vigour to conditions at HU10; however, this was

consistent with Drever and Lertzman (2001), who reported greater log radial growth at site series 05 than 01 at equivalent light levels. Average stem volume increment of Douglas-fir ranked second only to western hemlock. When gap T was at a maximum, actual and modelled stem volume increased to a maximum at ~35 m into the gap. Low moisture stress during the growing season possibly accounted for the increases in stem volume for this species, even if maximum light levels were suboptimal for maximum growth; however, this does not explain why all other species on the site did not benefit in the same way.

As a shade-tolerant species, western redcedar is capable of near maximum growth at T values below 0.6 (Drever and Lertzman 2001); however, our data described a relatively poor response on this site, which is difficult to explain. Perhaps site climate differences were in part responsible for the response on this site, Wright et al. (1998) showed that the shapes of species-specific light response curves could shift among the different climatic regions in north-western British Columbia. At the HU10 site, expected relative rankings for shade tolerance (Carter and Klinka 1992) are reversed for western redcedar and Douglas-fir: western redcedar seems to behave more like a light-requiring, shade-intolerant species. Carter and Klinka (1992) also reported that western redcedar had higher relative height increments on sites with drier moisture regimes. Vapour pressure deficit during the growing season was generally moderate at the HU10 site, and possibly benefitted western redcedar. Weak establishment owing to poor stock or handling must be considered; however, the seedlot planted at the HU10 site was the same as at GS10, although a smaller stock type (PSB 1+0, 412A) and different grower (Appendix 1) were used; only one individual did the planting; and the stock was handled appropriately. Physiological differences resulting from nursery culture are possible but not likely. No significant non-conifer vegetation competition was evident on the HU10 site, but the vigorous western hemlock regeneration increased annually. Soil nutrient levels were not analyzed. Nitrogen levels may interact with light levels to affect photosynthesis and growth (Kranabetter 2008), and may be interacting with the effects of vapour pressure and root competition (Wang et al. 1994); however, it is surprising that only one species would be affected. Another possibility is that the site's degree of wetness and waterlogging during the winter and spring may affect early growth (Klinka and Brisco 2009). Stem sweep was noted for western redcedar, probably from snowpress on the 20% slope, that may have had some effect on stability and growth. Stem form was generally good for the other species. Some browsing occurred for several years after planting (Table 8), despite applications of Plantskydd. About 23% of western redcedar seedlings suffered some browsing in the first year, and 5–12 % in subsequent years. Douglas-fir was less affected, but western hemlock and western white pine were browsed 23% and 46%, respectively, in the first year. Browsing of western redcedar continued at a low level in subsequent years, but western hemlock was not similarly affected. If such continuous browsing results in growth retardation, then it is possible that browsing contributed to the poor performance of western redcedar. No evidence in the literature points to Plantskydd causing growth retardation in western redcedar, but it is one more variable that must be considered. Western white pine was severely browsed in the planting year and subsequently, but its performance was not much different from pine plantings at the fenced GS10 site. If browsing is indeed a significant factor that affects growth, subse-

quent growth measurements will show whether western redcedar will recover and perform as expected relative to the other three species.

Seedling mortality was low on the HU10 site—6% or less—and mortality in the gap area was not consistently different from that under the residual stand. This suggests that transmitted light levels were not necessarily important to seedling survival when combined with the soil moisture deficit periods at the site. Because western hemlock and Douglas-fir, the two most vigorous species on this site, had the highest overall mortality, it is unlikely that mortality is strongly influenced by the site's moisture stress pattern, which was affected mainly by underground root competition and evaporative demand. Furthermore, the shade-tolerance ranking of these species (Douglas-fir: lower; western hemlock: higher) suggests that there was no pattern of species-dependent mortality with light. However, the mortality ranking at both gaps was the same, which suggests that the conditions at HU10 simply had less effect on the relative susceptibility to drought for each species.

4.3 TASS III Estimates

Comparisons by location between field (corrected hemispherical photos) and modelled (TASS) estimates of T (Figures 17 and 18) indicated that the light model TRAYCI in TASS differs to some degree from the hemispherical photo estimates corrected using hourly averages from regularly calibrated quantum sensors. For the GS10 site, TASS estimates of T were somewhat greater than the hemispherical photo estimates on the south side of the gap and lower to the east and west. The linear regression fit was fairly good at the centre row, and the overall regression fit was adequate (adjusted $R^2 = 0.88$). For the HU10 site, TASS estimates of T were greater than the hemispherical photo estimates on the south side of the gap and at the centre, but were close on the north edge. The linear regression fit between the two estimates was displaced from the origin but was almost parallel. This difference in T estimates may be linked to the chosen canopy coefficients or an error in allowing for the slope, or they could be related to the fact that the TRAYCI model used in TASS estimated open sky conditions, while SLIM used actual measured open sky PPFD values for these calculations. Comeau (P. Comeau, pers. comm. Feb. 28, 2013) has noted that estimation of transmittance values from hemispherical photographs is sensitive to assumptions about open sky conditions, particularly when dealing with small to moderate gaps in conifer stands.

5 SUMMARY

This study examined the growth of Douglas-fir, western hemlock, western redcedar, and western white pine across a canopy gap of about 0.5 ha. The overall objective was to explore the effect of the stand edge on the growth of conifers with different shade-tolerance rankings at two sites that represented the drier and wetter variants of the CWH1xm subzone. The gaps were created as part of a group selection silvicultural system that emulates the variation in forest structure and openness as would occur naturally in this zone.

At GS10 and HU10, the light environment of each seedling was characterized using hemispherical photographs. In addition, instruments were installed to measure transmitted light, temperature, rainfall, soil moisture,

and vapour pressure deficit across both gaps. Data for at least five growing seasons (April 1–October 31) were presented for both sites.

The GS10 site, located on a 01 site (HwFd – *Kindbergia*) in the drier CWIxm1, had relatively shallow gravelly soils, whereas the HU10 site, located on a 05 site (Cw – *Sword fern*) in the wetter CWIxm2, had deeper, wetter soils. The two sites, as expected, varied in microclimate.

Maximum transmittance of above-canopy light (T) at GS10 and HU10 was approximately 0.8 and 0.7, respectively, and minimum levels in the understorey declined to less than 0.05 at both sites on the south side of the gaps. Transmitted light at HU10 was lower at the south edge compared to GS10 and at all equivalent positions to the north edge by between 30 and 40%. Transmitted light levels in the north residual stands at the two sites were relatively similar. Several important differences between the two gaps contributed to the observed differences in transmitted light. The residual stand canopy at HU10 is denser than that at GS10 due to the predominance of western hemlock. Trees at the south edge are approximately 10 m taller than those at GS10, and because the terrain slopes down towards the north at about 20%, tree shadows are lengthened, which makes the gap behave as if the trees were even taller (Spittlehouse et al. 2004).

Light modelling with TASS III revealed both differences and similarities between the modelled values and estimates derived from hemispherical photos. Some differences would have been expected given that the light model in TASS (TRAYci) estimated light levels by using estimated above-canopy light levels and a modelled canopy, whereas hemispherical photos were provided with measured above-canopy light levels. Both methods made assumptions about the amount of diffuse and beam light.

Growth on the sites was affected by both soil moisture and vapour pressure deficit. The rainfall sums at STEMS 2 for the five measurement years were 45% greater than those at STEMS 1. Consequently, soil moisture characteristics were very different between the GS10 and HU10 gaps. Soils generally began to dry out in June and would pass through several wetting and drying cycles into October. The soils under the residual canopy dried out first and rehydrated last; the gaps remained wet longer. This pattern was evident at both sites but much less so at HU10. In the first year at HU10 (2008), the soils never exhibited drying greater than the threshold of plant stress; in the gap, only the south edge began to exhibit a period of drying by the third year of measurement.

The north–south vapour pressure deficit profiles of the two gaps were very similar, especially under the residual canopy and at the north edge. The main difference between the gaps occurred within 6–20 m of the south edge. The vapour pressure deficit at GS10 was considerably greater than at HU10, with up to triple the number of hours when values exceeded the 2 kPa stress threshold. This was a result of the difference in shading by the residual stand near the south edge.

Growth tended to increase to a maximum at T values of ~ 0.3 and ~ 0.8 for western hemlock and western redcedar, respectively, and did not reach a maximum at 0.8 T for Douglas-fir and western white pine. Western hemlock grows vigorously at both sites. Mortality for this species was high in the residual stand at GS10 and highest of all species in the gap. Douglas-fir appeared to grow well at HU10, which was the moister, darker site, and western redcedar grew more vigorously at GS10, which was the dryer, brighter

site. Western white pine grew equally well at both sites and responded as a light-requiring species that has not received enough light to maximize growth. No seedlings should be planted under the residual canopy because all growing space would already be exploited by the existing stand; little growth could be expected from seedlings of these four species if planted within 3–5 m of the south edge or the north edge.

The period of dry soils increased in the first 2 years of measurement at GS10 as the competing vegetation (mainly salal and bracken fern) developed and remained fairly constant in subsequent years. Moisture deficits did not appear for 3 years after planting at HU10.

An additive model was used to incorporate the moisture variables with T estimates to model the effect of light on growth, although replication was considered insufficient for statistical comparisons between the two sites. The model indicated that light significantly affected growth at both sites for all species. Soil moisture and vapour pressure deficit also significantly negatively affected growth, except at GS10, where the effect of vapour pressure deficit was not significant for Douglas-fir and western hemlock.

Researchers who are interested in studying the regeneration of trees in gaps may consider the approach taken in this study valuable. This experimental approach involves monitoring environmental gradients that affect tree growth and development and relating those gradients to their growth response. Gaps have gradients of light, temperature, moisture, and probably nutrients, and our understanding of how these gradients interact to affect regeneration is fundamental to our understanding of gap systems. The seedling environment may be manipulated over time if necessary (i.e. with trenching and root wrenching) and individual tree development can be tracked in conjunction with micro-environmental data so that the hysteresis in development is known without having to sample destructively and retrospectively. Regenerating seedlings and surrounding canopy can be accurately mapped for spatially explicit modelling. One disadvantage of this approach is the considerable demand on resources to install and maintain the equipment and to collect and analyze the data. Extensive pre-planning is essential to determine what applications will work, their proper installation, and planning of time and adequate budget for proper maintenance. Some important improvements on the design of this study would include the following: the collection of soil and foliage nutrient data for inclusion in the model, orientation of the gaps with the cardinal points so that the north and south edges are properly aligned (desirable for light modelling), some measurement seedlings growing in a full light environment (not possible in a 0.5-ha gap), replicate gaps on the same site, and some variation in gap size (however, the monitoring would become prohibitive without staff and budget). Also, commencing study sites simultaneously is preferable to a staggered approach, although that was unavoidable in this study.

6 CONCLUSION

Microclimate and light assessments suggest that conifer seedling growth is a function of a combination of light, moisture, and temperature conditions that change depending on site and proximity to the residual stand and position

within gaps. The early 5-year results of this study indicate that a group selection system with gaps smaller than 0.5 ha may not provide adequate light for less shade-tolerant species such as Douglas-fir and western white pine to out-compete more shade-tolerant species such as western hemlock and western redcedar but that moisture differences can help compensate for lower light levels. Continued monitoring of these two sites, along with additional gap studies, will provide valuable information from which to explore forest gap regeneration dynamics and improve science-based decision-making regarding partial cutting silvicultural systems.

LITERATURE CITED

- British Columbia Ministry of Forests. 1995. Biodiversity Guidebook. For. Prac. Br., Min. For., Victoria, B.C. Forest Practices Code of British Columbia Guidebook.
- Brunner, A. 1998. A light model for spatially explicit forest stand models. For. Ecol. Manag. 107:19-46.
- Buckland, D.C. 1956. Terminal shoot growth of four western conifers for a single growing season. The Forestry Chronicle 32:397-399.
- Canham, C.D. 1988. An index for understory light levels in and around canopy gaps. Ecology 69:1634-1638.
- . 1995. GLI/C: software for calculation of light transmission through forest canopies using color fisheye photography. Inst. Ecosyst. Studies, Millbrook, N.Y.
- Canham, C.D., J.S. Denslow, W.J. Platt, J.R. Runkle, T.A. Spies, and P.S. White. 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Can. J. For. Res. 20:620-631.
- Carter, R.E. and K. Klinka. 1992. Variation in shade tolerance of Douglas-fir, western hemlock, and western redcedar in coastal British Columbia. For. Ecol. Manag. 55:87-105.
- Chen, J.M., T.A. Black, and R.S. Adams. 1991. Evaluation of hemispherical photography for determining plant area index and geometry for a forest stand. Agric. For. Meteorol. 56:129-143.
- Chen, J., J.E. Franklin, and T.A. Spies. 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agric. For. Meteorol. 63:219-237.
- Christy, E.J. 1986. Effect of root competition and shading on growth of suppressed western hemlock (*Tsuga heterophylla*). Vegetatio. 65(1): 21-28.
- Cleary, B.D. and W.K. Ferrell. 1970. The effect of plant moisture stress on the physiology and establishment of planted Douglas-fir and ponderosa pine seedlings. PhD thesis. Oregon State Univ., Corvallis, Oreg.

- Coates, K.D. 2000. Conifer seedling response to northern temperate forest gaps. *Forest Ecology and Management* 127:249–269.
- Coates, K.D. and P.J. Burton. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. *Can. J. For. Res.* 29:1374–1382.
- Comeau, P.G. 2000. Measuring light in the forest. B.C. Min. For., Victoria, B.C. Exten. Note 42. www.for.gov.bc.ca/hfd/pubs/Docs/En/En42.pdf (Accessed Oct. 2012).
- Comeau, P.G., E. Gendron, and T. Letchford. 1998. A comparison of several methods for estimating light under a paper birch mixedwood stand. *Can. J. For. Res.* 28:1843–1850.
- Comeau, P.G., R. Macdonald, and R. Bryce. 2002. SLIM version 2.1i (Spot Light Interception Model). B.C. Min. For., Victoria, B.C.
- Comeau, P.G., R. Macdonald, R. Bryce, and B. Groves. 1998. LITE: a model for estimating light interception and transmission through forest canopies. Users manual and program documentation. B.C. Min. For., Victoria, B.C. Work. Pap. 35. www.for.gov.bc.ca/hfd/pubs/docs/wp/wp35.htm (Accessed Oct. 2012).
- DeLong, D., P.G. Comeau, I. Cameron, P. Simpson, R. Adams, and E. Fanjoy. 2002. How light conditions affect tree seedling performance in the Interior Cedar–Hemlock subzone: preliminary results-EP 1191. B.C. Min. For., Nelson Forest Region, Nelson, B.C. Exten. Note 050. www.for.gov.bc.ca/rsi/research/nextnotes/En050.htm (Accessed Oct. 2012).
- de Montigny, L. 2004. Silviculture Treatments for Ecosystem Management in the Sayward (STEMS): establishment report for STEMS 1, Snowden Demonstration Forest. B.C. Min. For., Victoria, B.C. Tech. Rep. 017. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tro17.pdf (Accessed Oct. 2012).
- . 2009. Silviculture Treatments for Ecosystem Management in the Sayward (STEMS): establishment report for STEMS 2, Elk Bay. B.C. Min. For., Victoria, B.C. Tech. Rep. 049. www.for.gov.bc.ca/hfd/pubs/Docs/Tr/Tro49.pdf (Accessed Oct. 2012).
- Dignan, P. and L. Bren. 2003. Modelling light penetration edge effects for stream buffer design in mountain ash forest in southeastern Australia. *For. Ecol. Manag.* 179:95–106.
- Drever, C.R. and K.P. Lertzman. 2001. Light-growth responses of coastal Douglas-fir and western redcedar saplings under different regimes of soil moisture and nutrients. *Can. J. For. Res.* 31:2124–2133.
- Easter, M.J. and T.A. Spies. 1994. Using hemispherical photography for estimating photosynthetic photon flux density under canopies and in gaps in Douglas-fir forests of the Pacific Northwest. *Can. J. For. Res.* 24:2050–2058.
- Fielder, P. and P. Comeau. 2000. Construction and testing of an inexpensive PAR Sensor. B.C. Min. For., Victoria, B.C. Work. Pap. 53. www.for.gov.bc.ca/hfd/pubs/docs/wp/Wp53.pdf (Accessed Oct. 2012).

- Franklin, J.F. and C.T. Dyrness. 1973. Natural vegetation of Oregon and Washington. U.S. Dep. Agric. For. Serv. Pac. NW Res. Sta., Portland, Oreg. Gen Tech. Rep. PNW-GTR-008.
- Frazer, G.W., P.A. Fournier, J.A. Trofymow, and R.J. Hall. 2001. A comparison of digital and film fisheye photography for analysis of forest canopy structure and gap light transmission. *Agric. For. Meteorol.* 109:249-263.
- Gendron, F., C. Messier, and P.G. Comeau. 1998. Comparison of various methods for estimating the mean growing season percent photosynthetic photon flux density in forests. *Agric. For. Meteorol.* 92:55-70.
- Gray, A.N., T.A. Spies, and M.J. Easter. 2002. Microclimate and soil moisture responses to gap formation in coastal Douglas-fir forests. *Can. J. For. Res.* 32:332-343.
- Groot, A. 2004. A model to estimate light interception by tree crowns, applied to black spruce. *Can. J. For. Res.* 34:788-799.
- Hastie, T.J. and R.J. Tibshirani. 1990. Generalized additive models. Chapman and Hall, New York, N.Y.
- Khan, S.R., R. Rose, D.L. Haase and T.E. Sabin. 1996. Soil water stress: Its effects on phenology, physiology, and morphology of containerized Douglas-fir seedlings. *New Forests.* 12:19-39.
- Klinka, K. and D. Brisco. 2009. Silvics and silviculture of coastal western redcedar: a literature review. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. Spec. Rep. Ser. 11. www.for.gov.bc.ca/hfd/pubs/Docs/Srs/Srs11.pdf (Accessed Oct. 2012).
- Klinka, K., Q. Wang, G.J. Kayahara, R.E. Carter, and B.A. Blackwell. 1992. Light-growth response relationships in Pacific silver fir (*Abies amabilis*) and subalpine fir (*Abies lasiocarpa*). *Can. J. Bot.* 70:1919-1930.
- Kranabetter, J.M. 2008. Interacting effects of soil nitrogen supply and light availability on understory sapling growth and foliar attributes. PhD thesis. Univ. British Columbia, Vancouver, B.C.
- Krasowski, M.J. and J.N. Owens. 1991. Growth and morphology of western redcedar seedlings as affected by photoperiod and moisture stress. *Can. J. For. Res.* 21:340-352.
- Lieffers, V.J., C. Messier, K.J. Stadt, F. Gendron, and P.G. Comeau. 1999. Predicting and managing light in the understory of boreal forests. *Can. J. For. Res.* 29(6):796-811.
- Lindh, B.C., A.N. Gray, and T.A. Spies. 2003. Responses of herbs and shrubs to reduced root competition under canopies and in gaps: a trenching experiment in old-growth Douglas-fir forests. *Can. J. For. Res.* 33:2052-2057.
- MacFarlane, D.W., E.J. Green, A. Brunner, and R.L. Amateis. 2003. Modeling loblolly pine canopy dynamics for a light capture model. *For. Ecol. Manag.* 173:145-168.

- Mailly, D. and J.P. Kimmins. 1997. Growth of *Pseudotsuga menziesii* and *Tsuga heterophylla* seedlings along a light gradient: resource allocation and morphological acclimation. *Can. J. Bot.* 75:1424-1435.
- Mitchell, A. K., and J.T. Arnott. 1995. Effects of shade on the morphology and physiology of amabilis fir and western hemlock seedlings. *New Forests*. 10:79-98.
- Mitchell, K.L. 1975. Dynamics and simulated yield of Douglas-fir. *For. Ecol. Monogr.* 17.
- Nobis, M. and U. Hunziker. 2005. Automatic thresholding for hemispherical canopy-photographs based on edge detection. *Agric. For. Meteorol.* 128:243-250.
- Pacala, S.W., C.D. Canham, and J.A. Silander, Jr. 1993. Forest models defined by field measurements: 1. The design of a northeastern forest simulator. *Can. J. For. Res.* 23:1980-1988.
- Pojar, J., K. Klinka, and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. *For. Ecol. Manag.* 22:119-154.
- SAS Institute Inc. 2004. SAS OnlineDoc™ 9.1.3 SAS Institute Inc., Cary, N.C.
- Simpson, G.M. 1981. Water stress on plants. Praeger Publishers, New York, N.Y.
- Smith, D.M. 1986. The practice of silviculture. 8th ed. John Wiley & Sons Inc., New York, N.Y.
- Spitters, C.J.T., H.A.J.M. Toussaint, and J. Goudriaan. 1986. Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis. Part I. Components of incoming radiation. *Agric. For. Meteorol.* 38:217-229.
- Spittlehouse, D.L., R.S. Adams, and R.D. Winkler. 2004. Forest, edge, and opening microclimate at Sicamous Creek. B.C. Min. For., Victoria. B.C. Res. Rep. 24. www.for.gov.bc.ca/hfd/pubs/Docs/Rr/Rr24.pdf (Accessed Oct. 2012).
- Stadt, K.J., V.J. Lieffers, and B.D. Pinno. 2001. Modelling light dynamics in boreal mixedwood forests. SFM network project: spatially-explicit calibration of a light model for eastern and western boreal forests. Univ. Alberta, Sustainable For. Manag. Netw., Edmonton, Alta. Project Final Rep. 2001-12.
- Temesgen, H. and K. Gadow. 2004. Generalized height-diameter models: an application for major tree species in complex stands of interior British Columbia. *Eur. J. For. Res.* 123(1):45-51.
- Voicu, M.E. and P.G. Comeau. 2006. Microclimatic and spruce growth gradients adjacent to young aspen stands. *For. Ecol. Manag.* 221:13-26.
- Walters, J., and J. Soos. 1963. Shoot growth patterns of some British Columbia conifers. *Forest Science* 9:73-85.

- Walters, M.B., C.C. Lajzerowicz, and K.C. Coates. 2006. Soil resources and the growth and nutrition of tree seedlings near harvest gap-forest edges in interior cedar-hemlock forests of British Columbia. *Can. J. For. Res.* 36(1):62-76.
- Wang, G.G., H. Quian, and K. Klinka. 1994. Growth of *Thuja plicata* seedlings along a light gradient. *Can. J. Bot.* 72:1749-1757.
- Williams, C.B. Jr. 1968. Seasonal growth of upper-slope conifers. Research Paper PNW-62. United States Department of Agriculture (USDA), For. Serv., Pac. NW For. and Range Exper. Sta., Portland, Oreg.
- Wood, S. 2006. Generalized Additive Models: an introduction to R. Chapman and Hall/ CRC. Boca Raton, Fla.
- Wright, E.E., K.D. Coates, C.D. Canham, and P. Bartemucci. 1998. Species variability in growth response to light across climatic regions in north-western British Columbia. *Can. J. For. Res.* 28:871-886.
- York, R.A., R.C. Heald, J.J. Battles, and J.D. York. 2004. Group selection management in conifer forests: relationships between opening size and tree growth. *Can. J. For. Res.* 34:630-741.

APPENDIX 1 Species and stock types planted in the three light study gaps

TABLE A1.1 Species, seedlot, and stock type information for seedlings planted in the GS10 (Snowden Demonstration Forest), HU10 (Elk Bay), and Gray Lake (PP10) light study gaps^a

Planted area	Plant date	Request key	Stock type	Seedlot	Nursery	Species ^b	Genetic gain
GS10	2004	2003DCR0029	PSB1+0 415D	61173	K&C Silviculture	Cw	G+02
GS10	2005	2004DCR0036	PSB1+0 415D	6755	PRT Campbell River	Cw	G+02
HU10	2006	2005DIC0135	PSB1+0 412A	61173	Woodmore	Cw	G+02
PP10	2009	2009DCR0902	PSB1+0 415D	61173	Cowichan Lake Res Stn	Cw	G+02
GS10	2004	2003DCR0022	PSB1+0 415D	60583	PRT Campbell River	Fd	G+07
GS10	2005	2004DCR00	PSB1+0 415D	61088	Arbutus Grove	Fd	G+12
HU10	2006	2005DCR0116	PSB1+0 412A	61284	Arbutus Grove	Fd	G+10
PP10	2009	2009DCR0903	PSB1+0 415D	60583	Cowichan Lake Res Stn	Fd	G+07
GS10	2004	2003DCR0028	PSB1+0 415D	60676	BC Forest Service	Pw	R+50
GS10	2005	2004DCR0034	PSB1+0 415D	43590	PRT Campbell River	Pw	G+02
HU10	2006	2005DSI0068	PSB1+0 412A	61094	Sylvan Vale	Pw	—
PP10	2009	2009DCR0901	PSB1+0 415D	60676	Cowichan Lake Res Stn	Pw	R+50
GS10	2004	2003DPM0018	PSB1+0 412A	6766	BC Forest Service	Hw	G+02
GS10	2005	2004DCR00	PSB1+0 412A	60224	Arbutus Grove	Hw	G+02
HU10	2006	2005DSI0180	PSB1+0 412A	61223	Arbutus Grove	Hw	G+13
PP10	2009	2009DCR0904	PSB1+0 412A	6766	Cowichan Lake Res Stn	Hw	G+02

^a Seed planning zone for all locations is "Maritime."

^b Cw: western redcedar; Fd: Douglas-fir; Pw: western white pine; Hw: western hemlock.

APPENDIX 2 TASS III settings to run *trayci* (light model)

TABLE A2.1 TASS III settings to run *trayci* (light model) and predict growing-season *T* values for the GS10 and HU10 gaps

TASS III attribute	TASS setting for GS10	TASS setting for HU10
Height—sensor (m)	1.3 (1 cm above leader)	1.5
Height—seedling leader (m)	1.2	1.2
Rotation of gap from north (°)	32	25
Ray tracing increments (°)	1	1
Length of season (day of year)	91–304	91–304
Latitude (°)	50	50

Root collar diameter (rcd): Measurements are to be made to the nearest 0.1 mm.

Diameter at breast height (dbh): Diameter at breast height for all stems greater than 1.3 m. Measurements are to be made to the nearest millimetre.

Vertical height (vht): Vertical height for all stems. Hemlock will be measured to top of the "droop" (i.e., the highest point of the seedling). The true stem length of leaning trees can be corrected in the future using the lean code entry (see below). Measurements are to be made to the nearest centimetre.

Total hemlock height (them): For hemlock only; a stem length measurement from the ground line to the end of the leader with the "droop" straightened. Measurements are to be made to the nearest centimetre.

Height to base of the crown (hbc): Height from the ground to the base of the crown. The base of crown for this measurement is defined as the first live leaf, needle, or branch. Measurements are to be made to the nearest centimetre.

Height to base of live crown (hlc): Height from the ground to the base of the live crown. The base of the live crown for this measurement is defined as the lowest point on the bole with live branches originating in at least three quadrants, exclusive of epicormic branching. Measurements are to be made to the nearest centimetre.

Crown radii in E W S N (cr_e, w, s, n): Crown radii in the four cardinal directions (east, west, south, north). Measurements are to be made to the nearest centimetre.

The following category coding is required on all tagged trees at the light study gaps. All records should have a "healthy," "alive," or "none" code, if such is the case.

Survival code (sur): 0=alive, 1=dead, 2=pulled out, 3=missing, 4=poor vigour, 5=good vigour

Leader codes 1 and 2: H=healthy, C=curled, F=forked, M=multiple leader, B=browsed, T=dead terminal bud, S=snapped/broken, A=absent, Z=stunted needles, O=other (specify)

Leader damage code 1 and 2: A=none, M=mechanical, S=falling slash (human), X=falling debris, F=climate-frost, N=snowpress, V=vegetation press, W=climate-drought, R=rodents, B=big game, F=fire, I=insects, D=disease, O=other (specify), U=unknown

Foliage codes 1 and 2: H=healthy, Y=chlorotic, M=mottled, N=necrotic, A=needles absent/defoliated, B=browsed, D=dead buds on laterals, L=lammas growth, O=other (specify)

Foliage damage code 1 and 2: A=none, M=mechanical, S=falling slash (human), X=falling debris, E=climate-frost, N=snowpress, V=vegetation press, W=climate-drought, R=rodents, B=big game, F=fire, I=insects, D=disease, O=other (specify), U=unknown

Degrees of lean (lean): Angle of lean from the vertical if greater than 10°.

Remarks: Any relevant comments or extra coding if no space under codes.

Date: YYYY/MM/DD

Sequence: Numbered field position of seedlings (when numbers are not consecutive).

```

proc gam data=EP1213lg.gsmodel3;
  by spc;
  model lsvincr_o8=param(sdry_avg vdayp) spline(gspacl_avg);
  score data=gsmolval out=predictions;
  *this outputs predicted values for logstem volume;
  output out=lgsgamstvi pred;
  ods output parameterestimates=parms;
run;

data manipulate; *rearranging dataset of parameter estimates;
  set parms;
  by spc;
  retain;
  if first.spc then do;
    coef_sdry=0; coef_vday=0; coef_pacl=0;
  end;
  if parameter='sdry_avg' then coef_sdry=estimate;
  if parameter='vdayp' then coef_vday=estimate;
  if parameter='Linear(gspacl_avg)' then coef_pacl=estimate;
  if last.spc then output;
  keep spc coef_sdry coef_vday coef_pacl;
run;

data together; *creating partial residuals and marginal predictions;
  merge manipulate /*lgsgamstvi*/gsgamstvi;
  by spc;
  residual=lsvincr_o8-p_lsvincr_o8; *raw residual (i.e. observed-fitted);
  fit_pacl=p_gspacl_avg+coef_pacl*gspacl_avg; *coefficient from output;
  part_pacl=residual+fit_pacl; *partial residual for pacl term;
  fit_vdayp=coef_vday*vdayp;
  part_vdayp=residual+fit_vdayp;
  fit_sdry_avg=coef_sdry*sdry_avg;
  part_sdry_avg=residual+fit_sdry_avg;
run;

```

¹ Program created by Peter Ott, Biometrician, B.C. Ministry of Forests, Lands and Natural Resource Operations.

TABLE A5.1 *Types of data, variables used, nature of raw data, and modified and summary files*

Data type	Variables	Raw data collection and storage	Modified files	Summary files
Climate and microclimate	Light: (PPFD) hourly averages ($\mu\text{mol}/(\text{m}^2\cdot\text{s}^{-1})$), daily totals ($\text{mol}/\text{m}^2$ per day). Temperature: ($^{\circ}\text{C}$) of air (at 150 cm) and soil (at 10 and 30 cm). Daily averages, maxima, and minima. Hourly recordings in gaps during the growing season. Relative humidity (stored as $\%/100$). Vapour pressure deficit: calculated in the data logger (unless problems with relative humidity or temperature). Daily averages, maxima, and minima. Hourly recordings in gaps during the growing season. No units. Soil moisture from moisture blocks: measured in ohms, which is converted to MPa in the data logger. Records maxima, minima, and averages once per day at midnight. Soil water content: $\text{m}^3(\text{water})/\text{m}^3(\text{soil})$. Records maxima, minima, and averages once per day at midnight.	Data loggers—Remote telemetry and field collections. All equipment installation, collection, and maintenance by Ministry staff. Storage in data loggers in ASCII table array type files. Require proprietary software to download. Downloaded as comma-delimited files (.dat). Raw files remotely downloaded directly to server. Field downloads to HP Palmtop and moved to server. Raw files backed up in a separate directory.	"Half-raw" files created at end of calendar year. Whole year's data appended into one file. Any gaps or errors in the time stamp, plus any other errors, are corrected.	Summary directories contain further treatment of the raw files. "Half-raw" temperature, relative humidity, vapour pressure deficit, soil moisture, and wind data are copied to an Excel spreadsheet for further corrections, charting, and summary. Final growing-season tabulated summaries are in separate spreadsheets. Light data are pre-processed in SAS to apply calibrations (if necessary) and the output copied to the Excel spreadsheet for charting and finally tabulated and graphed in the summary spreadsheet.

Continued on next page

Data type	Variables	Raw data collection and storage	Modified files	Summary files
Mapping	Co-ordinates (x, y, z) in metres of all residual trees and some of the seedling rows.	Data collected in the field using a Nikon "Total Station" theodolite by either Ministry staff or contract crews. Data saved in the theodolite and transferred to a laptop for downloading to the server. Data received on disk from contractor and transferred to the server. Storage of raw files as text files.	Raw files read into Excel for preprocessing. Missing seedling co-ordinates created for missing rows before saving as .csv files for reading into SAS for processing.	.xls and .csv files created. Some maps produced.
Modelling light in gaps	x, y, and z co-ordinates of seedlings and residual trees, height and diameter of residual trees at edge of gap.	Modified map data as above. Tree list data collected in the field and recorded in field instruments in text format. Only a sample (15%) of each residual tree species measured for crown and total height. Downloaded to server as text files or .xlsx files	Missing tree list data derived from an analysis using SAS to create predictive equations of height based on the sample diameter data.	Final complete map and tree list data file saved and given to the light modeller (Ken Poulson) to create the gap light estimates using TASS III.
Seedling data	Height (cm), diameter (mm) at ground level, crown radius (cm) in all four cardinal points, a number of condition and damage codes (see Appendix 3).	Field collection by contract crews using data entry devices. Data received on CD from contractor as either (or) text and .xls format and transferred to the server. Dave Goldie responsible for the contracts.	Data are checked and cleaned using SAS. Corrections made to SAS versions. Corrections to raw or SAS files documented in "readme" text files.	Summaries and analyses in SAS. Graphing in Sigmaplot.
Combined light and growth data	SAS was used to modify, correct, and combine light and growth data for analysis and graphing.			Output files in SAS database and .csv format for graphing and further analysis. Graphing in Sigmaplot.

APPENDIX 6 Vegetation control at the light study gaps

TABLE A6.1 *Vegetation control at each light study site*

Year	Site	Month brushed	Planting	Description of brushing treatment
2004	GS10	July	March	Salal trimmed over whole gap; below- ground component not completely removed.
2005	GS10		March	No treatments
2006	GS10	August		Vegetation clipped to about 10 cm in a 1-m strip each side of each N-S seedling row removed. Salal not treated (very low).
2006	HU10		February	No treatment
2007	GS10	June		Bracken fern and fireweed pushed over in 1-m area around each seedling.
2007	HU10			No treatment
2008	GS10	June		Bracken fern and fireweed pushed over in 1-m area around each seedling.
2008	HU10			No treatment
2009	GS10	September		Clearing of bracken fern, and fireweed to prevent press in the winter.
2009	HU10	May		Naturally regenerating western hemlock hand-pulled in a 1-m strip each side of each N-S seedling row.
2009	PP10		April	No treatment
2010	GS10	July		Bracken fern and fireweed beaten down around seedlings.
2010	HU10			No treatment
2010	PP10			No treatment

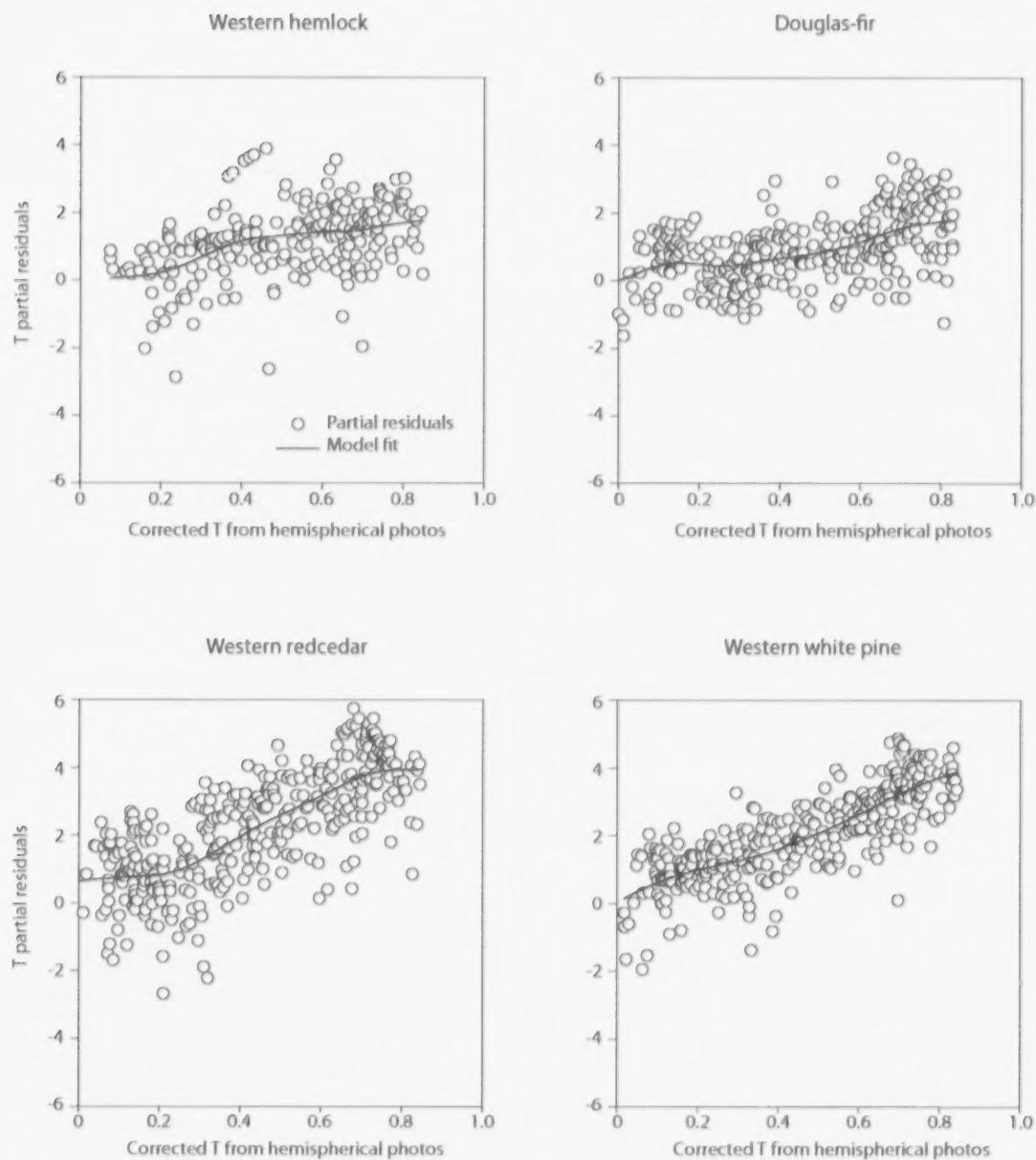


FIGURE A7.1 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2004–2008) corrected transmittance of above-canopy light (T) from hemispherical photos at the GS10 gap at STEMS 1. Circles are individual trees and the model is shown as a continuous line.

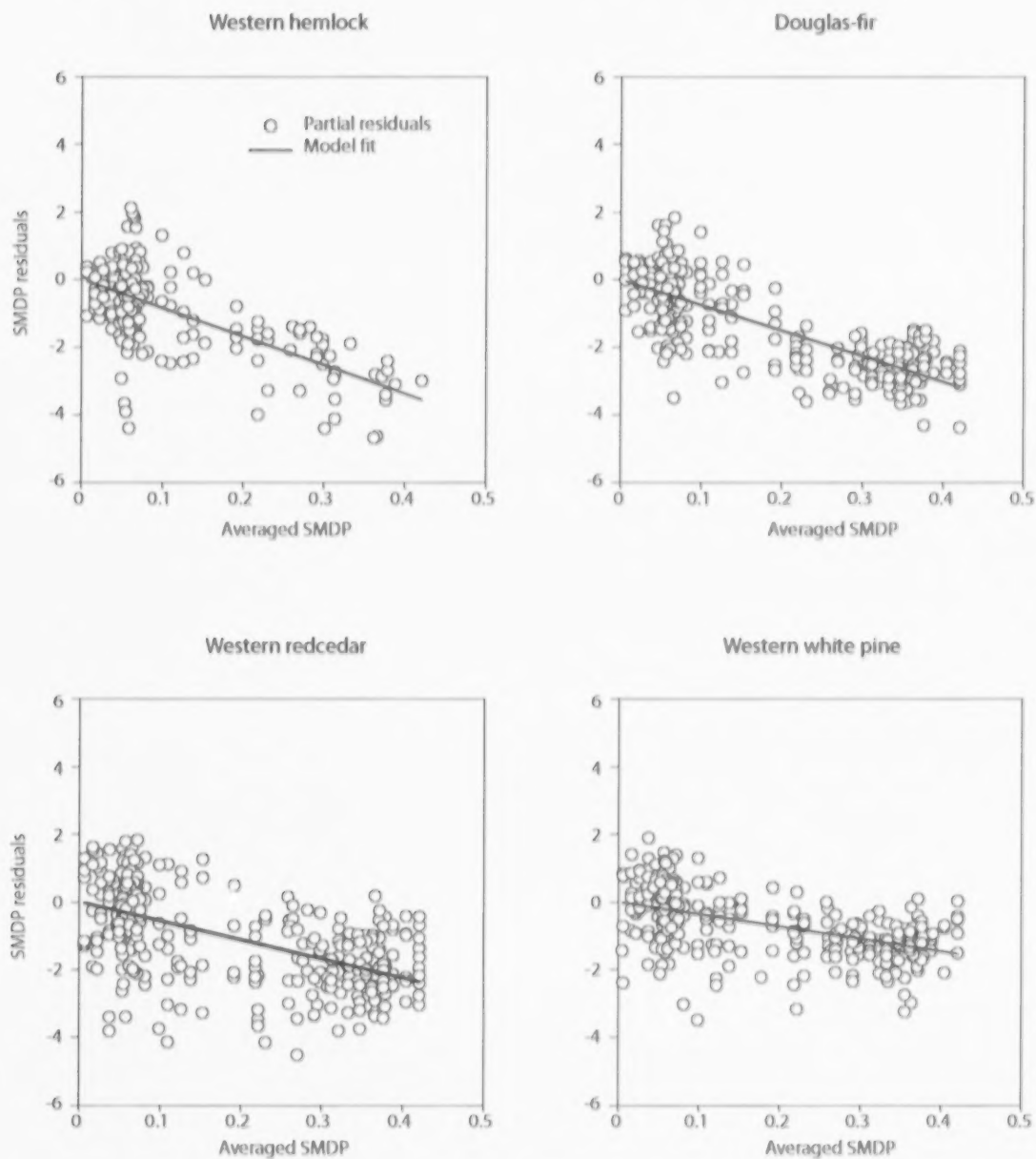


FIGURE A7.2 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2004–2008) soil moisture deficit period (SMDP) at the GS10 gap at STEMS 1. Circles are individual trees and the model is shown as a continuous line.

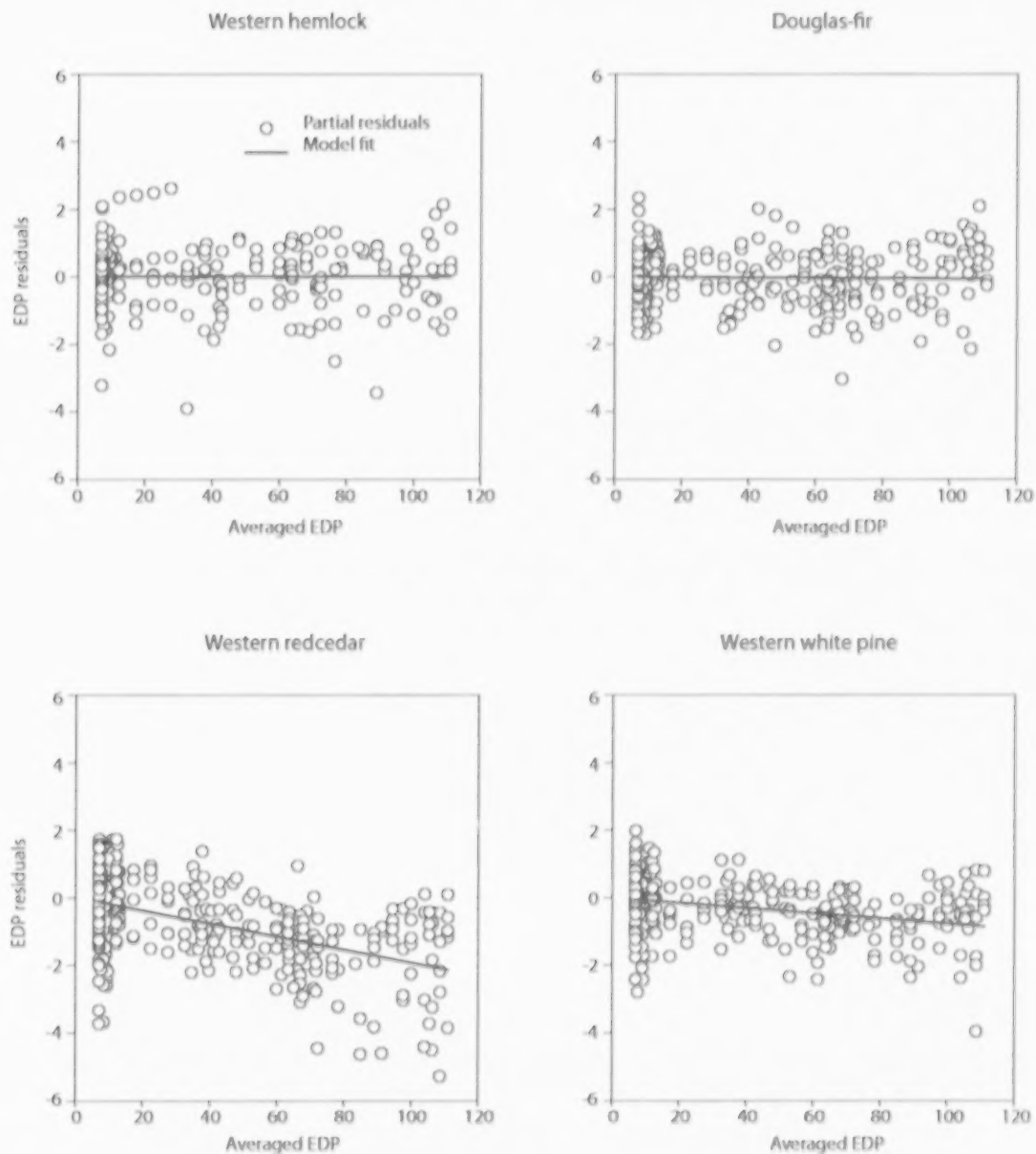


FIGURE A7.3 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2004–2008) evaporative demand period (EDP) at the GS10 gap at STEMS 1. Circles are individual trees, and the model is shown as a continuous line.

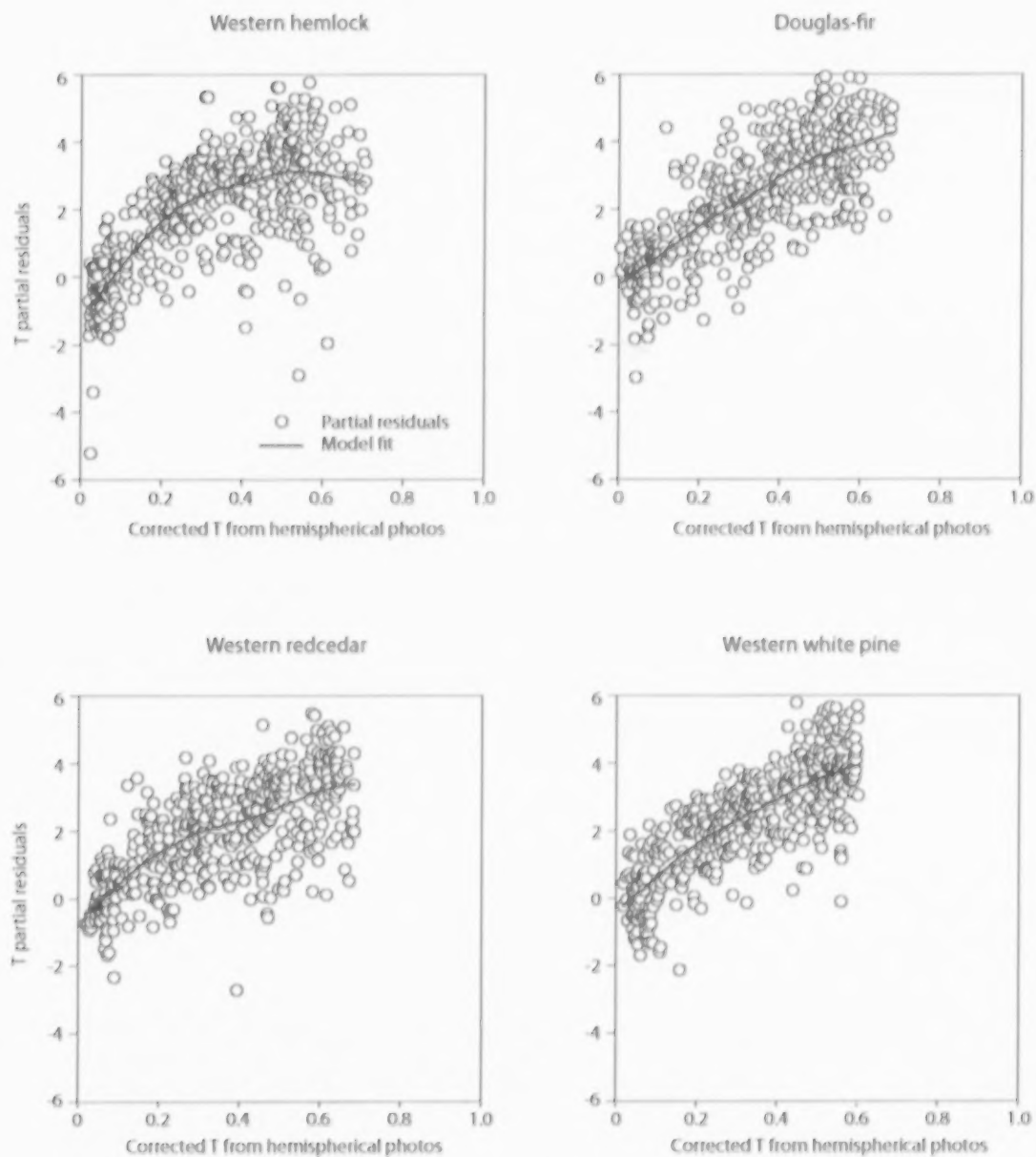


FIGURE A7.4 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2005–2010) corrected transmittance of above-canopy light (T) from hemispherical photos at the HU10 gap at STEMS 2. Circles are individual trees and the model is shown as a continuous line.

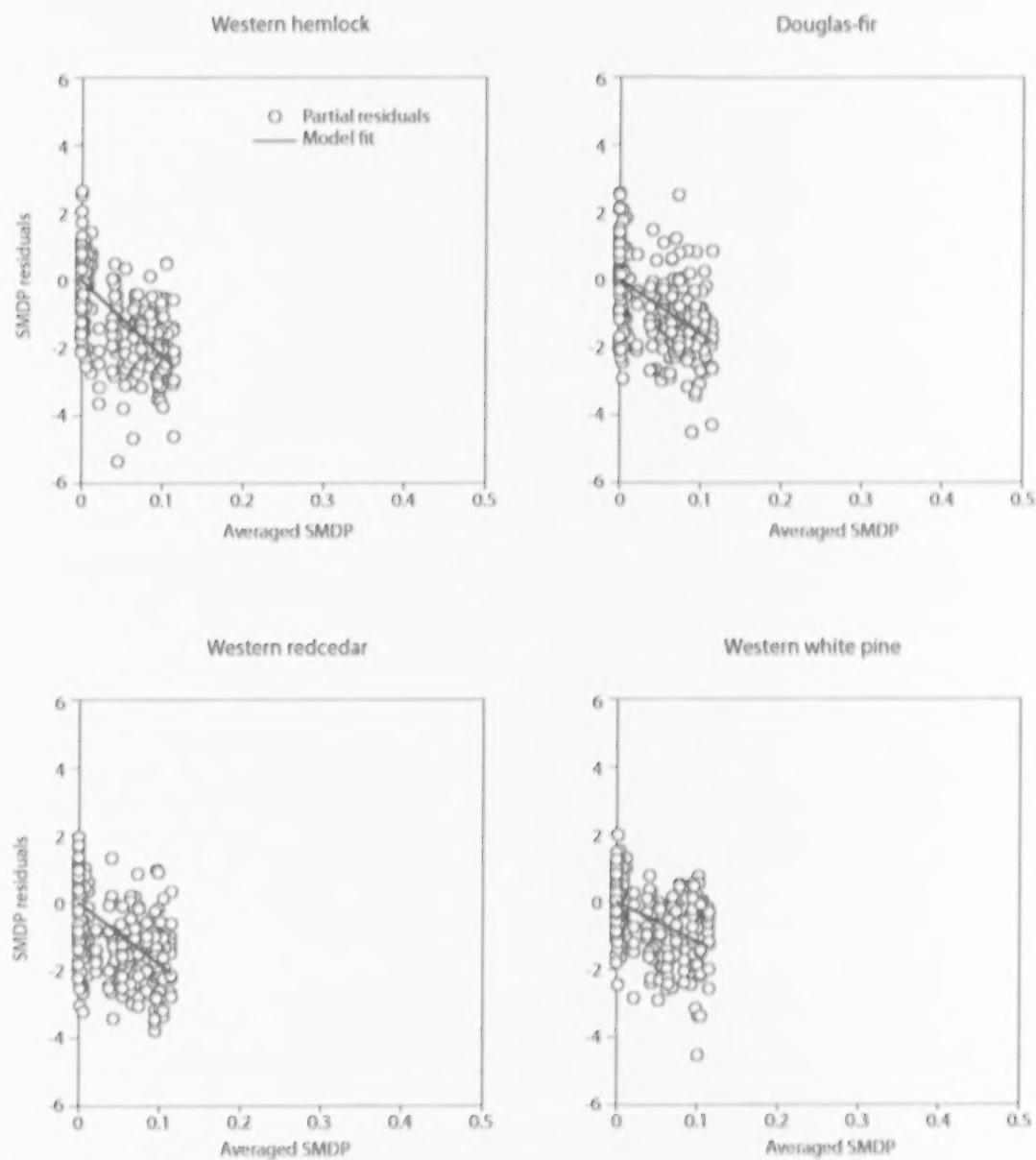


FIGURE A7.5 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2005–2010) soil moisture deficit period (SMDP) at the HU10 gap at STEMS 2. Circles are individual trees, and the model is shown as a continuous line.

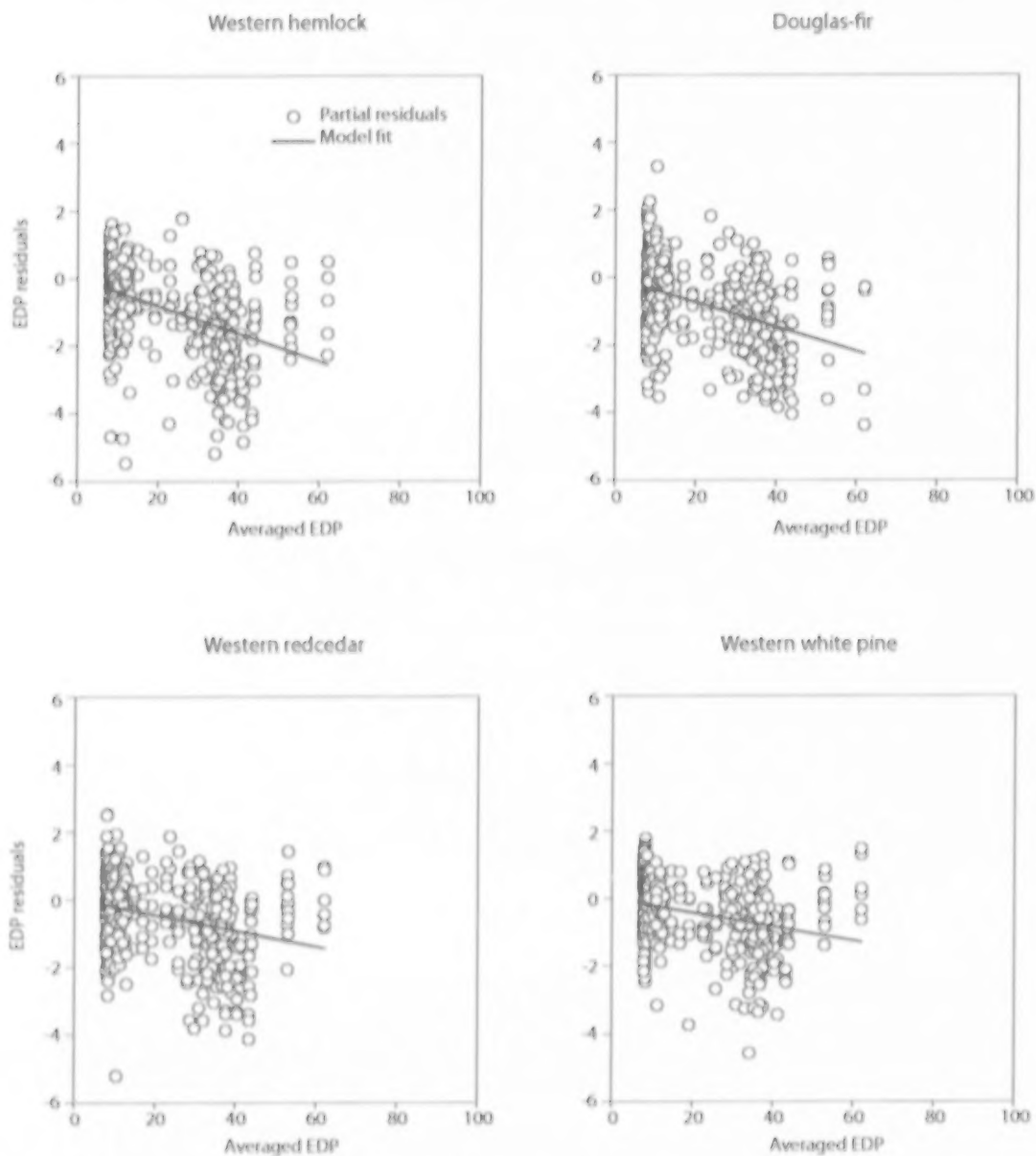


FIGURE A7.6 Partial residual plots of stem volume (cm^3) response of four species of conifer to averaged (2005–2010) evaporative demand period (EDP) at the HU10 gap at STEMS 2. Circles are individual trees, and the model is shown as a continuous line.